Understanding wood-pool dynamics using long-term monitoring data from the Gualala River Watershed: What can we learn?

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by

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Professor G. Mathias Kondolf, Chair
Professor Joe McBride
Professor John Radke

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Abstract

Understanding wood-pool dynamics using long-term monitoring data from the Gualala River Watershed: What can we learn?

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The complex interaction between processes governing water, sediment and wood drives channel morphology and aquatic habitat in forested riparian systems. Large in-stream wood plays an integral role in the ecology and integrity of forested riparian systems. In-stream wood can form stable structures that control local channel hydraulics and provide habitat for multiple aquatic species. The hydraulic diversity created by large wood in streams affects two major physical processes with key implications for aquatic biota: 1) local scour that leads to pool development, and 2) sediment deposition (and accumulation) that leads to bar formation. Both processes contribute to diverse habitats with structural complexity that many species rely on. Wood removal and harvest in the riparian zone disrupts the wood regime and affects the distribution and abundance of large wood in streams for years to come. Removing wood disrupts not only the wood regime but the hydro-geomorphic and biological processes that have adapted to it. The ecological importance of large wood as an in-channel element has become widely accepted in recent decades, leading many to advocate for re-placing large wood in streams and leaving riparian buffers to provide future large wood recruitment. As is the case with naturally contributed wood, channel response to artificially placed large wood is highly variable. The potential sources of variation are vast, difficult to pinpoint, and likely interact in ways that are not fully understood. Overall, very few analyses have been done which examine the 1) long-term wood-induced changes in channel morphology to 2) strategize placement of wood for restoration purposes, 3) in relation to the overall watershed context. Temporally and spatially appropriate monitoring data are needed to learn from past experience and improve future project design.

The Gualala River Watershed Council (GRWC) has been monitoring the locations and conditions of large wood and the surrounding channel morphology throughout their watershed since 1998. The monitoring data generated by this program represent a highly valuable long-term baseline dataset to evaluate the performance of large wood in streams, and to understand wood-pool relationships in the watershed that can guide future placement of large wood in the watershed. Salmonid habitat is limited in both quantity and quality in the Gualala River Watershed. Specifically, lack of in-stream wood and wood-formed pools has been identified as limiting factors. The primary objectives of this study were to: 1) characterize changes in the watershed over time with respect to wood and pools, 2) test the assumption that increases in wood are correlated with increases in pool habitat, and 3) assess whether reach-specific qualities may explain the observed variability in the wood-pool relationships.

This study confirmed that there are parts of the Gualala River Watershed that are increasing in both wood and pool abundance. At the aggregated watershed-scale, pool density was positively correlated with wood abundance (wood volume and wood density), pool area was negatively correlated with wood abundance, and maximum pool depth showed a slight negative correlation. Of the four reference reaches, LNF1 exhibited a positive relationship between all pool metrics and wood abundance. This may be partially explained by the size of the wood pieces relative to the channel cross-sectional area which suggests that the size of the wood piece relative to the channel cross-sectional area may be key to effective creation of wood-formed pools in this watershed. An analysis of wood locations along thalweg profile suggest that perhaps the concentration of the wood may be more important to pool formation than individual pieces dispersed throughout the reach. Overall, this study confirms the importance of conducting monitoring and analysis at multiple temporal and spatial scales.

From a restoration science standpoint, information on wood-pool dynamics may help GRWC and other practitioners understand the physical dimensions that lead to wood accumulations, and the relative importance of different reach-specific characteristics in facilitating pool formation using large wood. This information could be used to identify and prioritize portions of the channel network that are more conducive for creating pool habitat for anadromous salmonids, or for supporting other ecological functions.

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This thesis is thanks to you all.

SECTION 1

Wood in Rivers

Wood has been entering streams and rivers for more than 400 million years (Montgomery et al. 2003) and is a natural and vital component of riparian systems in forested watersheds. The complex interaction between processes governing water, sediment and wood drives channel morphology and aquatic habitat in forested riparian systems. In forested riparian systems, in-stream wood acts as a morphological forcing agent impounding sediment, redirecting stream flow, creating hydraulic diversity and otherwise contributing to stream heterogeneity which supports diverse aquatic biota (Figure 1-1).

1.1 What is Meant by “Large” and “Wood”

Common terminology for large in-stream wood often relates to the function that the piece plays, or describes its location relative to channel feature. Several terms are used when referring to “wood” in rivers. In a search of over 1,172 references, Gregory (2003) found at least 15 terms used in title of research papers (Table 1-1). In their meta-analysis, the research papers covered diverse study topics illustrating the diverse role wood plays in forested ecosystems.

Some controversy exists around the use of “debris” when referring to wood in rivers. “Debris” connotes something inconsequential or easily disposed of, which conflicts with the now widely accepted importance of wood in riparian ecosystems (Opperman et al. 2006). Terms such as terms “large wood,” “large in-stream wood,” “woody material,” “log jams” or “large wood structures” are emerging as more common in recent literature.

FIGURE 1-1.
Simplified conceptual framework for understanding the interconnection between water, wood, sediment, and habitat.

TABLE 1-1.

Examples of terms referring to wood in rivers.*

TERM USED	RELATED TO
Large organic material	Channel form and fluvial processes
Organic debris	Channel morphology and bedload transport Logging treatments and channel morphology Cutthroat trout
Organic debris dams	Role in streams
Large organic debris	Channel morphology
Obstructions	Sediment storage
Organic debris dams	Function of stream ecosystems Development, maintenance and role Effect of deforestation
Organic matter budgets	Stream ecosystems
Debris dams	River channel processes
Woody debris	Salmonid nursery streams Fish habitat Stream channel stability Pool formation Source of fine particulate organic matter Macroinvertebrates Fisheries and streamside management
Wood debris	Channel morphology and riparian areas
Coarse woody debris	Ecology in temperate ecosystems Ecological aspects Channel morphology
Logging debris	Dolly Varden population and macrobenthos
Large wood debris	Stream channel response Forestry and fishery interactions Dynamics in streams
Log steps	Geomorphic significance in forest streams
Organic matter storage	Spatial and temporal variation in headwater streams

*Modified from Table 1 in Gregory (2003).

The definition of "large" also varies among researches (Hassan et al. 2005); however, the 0.1 m diameter by 1 m length is a commonly used as the minimum threshold for defining large wood (Table 1-2).

TABLE 1-2.
Examples of minimum wood dimensions used to define large wood in rivers.

SOURCE	DIAMETER	LENGTH
Harmon et al. 1986	2.5 cm	[none specified]
Mellina and Hinch 2009*	10 cm	1 m
Lisle 1986a, 1995	10 cm	[none specified]
Dolloff 1994	10 cm [at the small end]	1.5 m
Keller and Swanson 1979	10 cm	[none specified]
Roni 2001	10 cm	1.5 m
Fetherston et al. 1995	10 cm	1 m
Smith et al. 1993	10 cm	1 m
Cordova et al. 2007	10 cm	1 m
Naiman et al. 2002	10 cm	1 m
Ralph et al. 1994	10 cm	3 m
Downie et al. 2006	30 cm	2 m
Berg et al. 1998	30 cm	3 m
Swanson 2003	10 cm	1 m
Flosi et al. 1998	12 in	6 ft
Williams and Morgan 2002	6 in	4 ft
Martin and Benda 2001	10 cm	1.5 m [in channels <5 m wide] 3 m [in channels >5 m]
Beechie and Sibley 1997	20 cm	3 m

*Based on Murphy et al. 1986, Murphy and Koski 1989, and Hassan et al. 2005

The supply and size of wood delivered to a channel defines a wood regime (Montgomery et al. 2003) which has significant effects on channel processes and therefore channel morphology (Figure 1-2). The primary mechanisms for wood delivery to aquatic ecosystems include:

Windfall:	Pieces of branches are broken from tree tops (also referred to as “blowdown”).
Mortality:	Trees fall into the channel as they senesce, or following a fire.
Bank erosion:	Adjacent trees fall into the channel due to bank erosion due to lateral movement of the river.
Mass wasting:	Downslope mass movement of rock and soil carries trees and other materials to the channel.

FIGURE 1-2.
Conceptual understanding of an undisturbed wood regime.

Most large wood enters streams from a relatively narrow band on either bank. In streams flowing through old-growth and second growth riparian zones in the Pacific Northwest, the majority of wood recruitment originated within 20–40 m of the channel (McDade et al. 1990, Benda et al. 2002, Benda et al. 2005). However, wood from distant floodplains and hillslope sources can be transported greater distances by floods or debris torrents (Harmon et al. 1986, Keller and Swanson 1979, Benda et al. 2002, Benda et al. 2005). Landslides may be the dominant recruitment mechanism in steep watersheds, while bank erosion may dominate in alluvial channels (Opperman et al. 2006). Recruitment rates vary depending on factors such as historical land use, stream size, and age, species and health of trees in the surrounding riparian zone (Keller and Swanson 1979).

1.2 The Role of Wood: Wood is Good.

Large in-stream wood plays an integral role in ecology and integrity of forested riparian systems. Large in-stream wood induces hydraulic, morphologic, and textural complexity (Abbe et al. 2003). The major importance of large wood lies in its structural characteristics and how they influence channel hydraulics (Bisson et al. 1987). In-stream wood can create pools, increase habitat diversity and complexity, reduce sediment transport, trap gravel needed for spawning, stabilize (or destabilize) streambanks, provide cover and refugia for fish, provide food for aquatic invertebrates, and provide stream nutrients and increasing overall stream productivity (Bilby and Likens 1980, Lisle 1986a, Bisson et al. 1987, Robison and Beschta 1990, Fausch and Northcote 1992).

1.2.1 Hydro-geomorphic Processes

In-stream wood can form stable structures that control local channel hydraulics and provide structural and habitat diversity necessary to support multiple aquatic species. Large in-stream wood can interact with the stream bed as a single piece (e.g., digger, spanner), or as part of larger accumulations (e.g., jam). The probability of log jam formation is influenced by many factors including the size of fallen trees relative to the channel, the supply of wood within the system, and channel substrate (Abbe 2000, Lancaster et al. 2001, Abbe and Montgomery 2003).

The hydraulic diversity created by large wood in streams affects two major physical processes with key implications for aquatic biota: 1) local scour that leads to pool development, and 2) sediment deposition (and accumulation) that leads to bar formation. Both processes contribute to diverse habitats with structural complexity.

Pool Formation

In forested streams, large wood structures are a principal mechanism for the formation of deep pools and islands in large channels. Many studies have found direct correlations between pool frequency and wood loading in plane bed, pool-riffle and forced pool-riffle channels (Montgomery et al. 1995). Pools form around in-channel obstructions that create friction and resist displacement by flowing water. Abbe and Montgomery (1996) found that large wood jams were a principal mechanism controlling reach-level habitat diversity through the formation of scour pools, bars and riparian forest refugia. Their research found that 70% of all pools were associated with log jams.

Pools develop around large wood in a variety of ways (Bisson et al. 1982). Plunge pools result when water flow scours sediment from the downstream side of in-stream wood that spans the channel, dam pools form when water is backed up behind one or more pieces, and backwater pools are created by eddies where the ends of pieces or rootwads jut into the flow. In general, the deepest pools form behind pieces that span the entire width of the channel near the water surface and are oriented perpendicular to flow (Cherry and Beschta 1989).

Sediment Regulation

Wood jams play a key role in regulating sediment by trapping sediment and buffering pulses of high sediment inputs. As trapped sediments accumulate, the streambed aggrades and allows for deeper pool formation. Raising the streambed also serves the purpose of bringing the channel into better equilibrium with its floodplain by increasing sediment deposition on the floodplain without interfering with coarse sediment transport in the channel. In addition, large wood helps stabilize banks and reduce excessive erosion.

The amount of sediment a wood jam might trap varies. A small wood jam might trap up to 5,000 cubic feet of sediment, whereas a larger wood jam might trap up to 30,000 cubic feet of sediment. In a study of Little Lost Man Creek (a tributary to Redwood Creek in northern coastal California), Keller et al. (2003) estimated that approximately 100 to 150 years of average annual bedload was stored in in-stream wood-related sites, with an additional 50 to 100 years of average annual bedload available for future storage.

The locations and principal roles of wood debris change throughout the river system (Bisson et al. 1987). The effects of large wood are greater small streams where wood can trap and store more sediment than the average annual rate of bedload transport (Marston 1982). In-stream accumulations of large wood in the headwaters that trap and store sediments may also result in the delay and dampening of flood peaks further downstream.

1.2.2 Species Benefits

In low- and mid-order forested streams large wood is the primary factor influencing aquatic habitat (Naiman et al. 2002). In-stream wood structures provide structural complexity, refugia, and sediment trapping that can benefit numerous biotic communities. Pools created by in-stream wood are essential for the life stages of many aquatic organisms, including anadromous fish that use wood-formed pools for refugia and rearing habitat.

Large wood provides two types of habitat within a stream: 1) the wood itself as a structural element, and 2) the wood-created environment (Maser and Sedell 1994). As a structural element, large in-stream wood provides cover from predators and refuge for juvenile and adult fish at a wide range of river flows. In addition, numerous species of insects use partially submerged wood to transition from their aquatic to their terrestrial life stages. Wood-formed pools provide areas of slack water where fish of all life stages can conserve energy. Adults lurk in pools with large wood cover, and then opportunistically dart into higher velocity areas after prey. In addition, the slow backwater areas provide refuge for fish during winter high flows, and wood-created pools provide essential habitat during summer when flows drop considerably. Within the pools themselves, pools of sufficient depth can provide multiple layers of fish habitat allowing for coexistence of multiple age classes or differing species. For example, juvenile coho are known to inhabit the water's surface and steelhead trout toward the head of the pool (Maser and Sedell 1994). Large wood aids nutrient cycling by trapping and storing organic matter in the stream channel allowing time for decomposition by microbes and insects. These functions are essential for many aquatic vertebrate and invertebrate species (Sedell and Beschta 1991). Large in-stream wood is therefore a vital contributor to the health of streams, rivers, estuaries and oceans (Maser and Sedell 1994).

1.2.3 Context Matters

Wood can influence watershed-scale patterns of erosion and sediment transport and can greatly influence channel response to disturbance (Montgomery et al. 2003); however, channel response to large wood is highly variable. Furthermore, response varies as you move from the piece of wood, to the reach, and then to the watershed (Table 1-3). Effects of woody debris on geomorphic processes can be misleading because they vary with the scale at which effects are considered, with characteristics of the channel, and with the size, density, and orientation of pieces (Lisle 1995).

In general, ecosystem type affects the quality and quantity of wood available to a stream, while variations in hydrology, forest type, and dominant erosion and transport processes are said to govern the spatial and temporal variability in wood recruitment, storage, and loss (Hassan et al. 2005). Log stability in channels likely depends on the physical characteristics of the piece relative to the channel, with more log movement occurring as channel width exceeds wood length (Hassan et al. 2005). The potential sources of variation are vast and difficult to pinpoint and

TABLE 1-3.
Generalized patterns of channel response to wood.

GENERALIZED PATTERN	SOURCE
At the Individual Piece/Pool Level	
Piece diameter was directly related to the ability of the piece to remain in a stable location, given a channel width.	Bilby and Ward 1989
Larger structures with a greater volume of wood created longer and deeper pools.	Beschta 1983
Pool area was positively correlated with the volume of wood anchoring the pool. The correlation improved with increasing channel width in streams up to approximately 20 m wide.	Bilby 1985
At the Reach Level	
Vertical changes in riverbed elevation due to deposition around or behind logjams were higher in confined channels, where there is little leeway for such channels to move laterally around the jams.	Montgomery et al. 2003
The greatest change in streambed elevation from log jam formation tended to occur in second to fourth order channels with bankfull widths less than the height of fallen trees, and valley gradients of 0.02–0.10.	Abbe 2000
In mountain channel networks, logjams can convert bedrock reaches to alluvial reaches by trapping bedload sediments.	Montgomery et al. 1996
Pool spacing (expressed as the number of channel widths between pools) decreased as the number of woody pieces increased. This relationship existed at both moderate-slope (0.02–0.05) and low-slope (0.001–0.02) channels, though the relationship was stronger in moderate-slope channels. Percent pool had a stronger relationship with woody volume in moderate-slope channels than in low-slope channels.	Beechie and Sibley 1997
Pool frequency increased with the number of debris accumulations.	Lisle and Kelsey 1982
There was a significant correlation between the number of pools and debris pieces in low gradient streams.	Grette 1985
Channel shape explained 30% of the variation in LWD volume, while LWD length and length:channel width combined, explained 72% of the variation in LWD density.	Cordova et al. 2007
At the Watershed Level	
The role of wood differed between small, medium, and large streams. In small streams, wood pieces themselves control the hydrological and sediment transfer characteristics. In medium streams, wood length and form are critical as wood accumulations form as a result of mobile pieces collecting behind key pieces. In large streams, wood dynamics vary with the geometry of the channel, channel pattern and distribution of flow velocities.	Gurnell et al. 2002
Low gradient reaches of Deer, Antelope and Mill creeks had tendencies toward pool filling and fine sediment accumulation.	Armentrout et al. 1998
There was a progressive decrease in wood load as a response to drainage area, elevation, channel width, bed gradient and total stream power suggesting that the intermediate size streams should have the maximum number of jams.	Wohl and Jaeger 2009

likely interact in ways that are not fully understood but widely acknowledged as important for understanding wood regimes.

1.3 Wood is Good? Past and Present Removal

Deliberate removal of large wood from streams has occurred on the west coast of the United States since the mid-1800s. "Stream cleaning"—the practice of deliberately removing in-stream wood—was a relatively common in the Pacific Northwest and North America (prior to the 1980s) (Mellina and Hinch 2009, Sedell and Luchessa 1981). Stream cleaning was carried out to enhance navigation, floodplain agriculture, log transportation, fish passage, water quality, and protect bridges, at a time when the ecological consequences for stream habitat were poorly understood (Sedell and Luchessa 1981).

1.3.1 Navigation

Individual wood pieces can be partial obstructions that create navigation hazards while large log jams can form full obstructions to navigation. Huge accumulations of woody material (up to 8 km long) were common and blocked navigation on most of the large rivers in the United States (Harmon et al. 1986). Around 1830, under the purview of the U.S. Army Corps of Engineers, "improvements" were initiated on the Mississippi River to clean rivers and streams of wood to maintain navigation

Wood jam on Big River. Historical photo courtesy of Klamath Resource Information System (KRIS).

(Harmon et al. 1986). Efforts were subsequently expanded to streams across the country, and from 1867–1920 many hundreds of thousands of snags, logs and wood piles were cleared from rivers all across the United States (Table 15 in Harmon et al. 1986).

1.3.2 Timber Harvest Practices

Navigability concerns were not only limited to watercraft. Rivers and streams were often the main artery for transporting wood as well. Wood would be floated downstream from harvest areas to lumber mills—a process referred to as a "log drive." While the drives themselves were responsible for significant damage to sensitive streambeds, banks, and riparian areas, the stream "improvements" that preceded these drives were equally if not more destructive (Dolloff 1994). In the low flow season prior to a "log drive" the stream was cleared of any obstructions. Obstructions such as floating trees, brush, and rocks, often caused serious and expensive log jams during the driving seasons. Extensive quantities of wood were removed from medium to large size streams (Sedell and Luchessa 1981). Boulders, large rocks, overhanging trees, submerged logs, or obstructions of any kind in the channel were hauled, burned, or blasted out of the way to ensure smooth, uninterrupted passage of harvested lumber.

"Splash damming" was a common practice used when natural flows were insufficient to transport logs, or where streams were too small to transport large logs (Bisson et al. 1987). Loggers would create a temporary dam across the stream to store wood and water until sufficient head was attained. By breaching the dam, the deluge would transport harvested logs to areas downstream where they could be easily transported and processed. The constant barrage of logs and water scraped away at the streambed and banks causing the channel to widen and severely modifying aquatic habitat. In extreme cases, the repeated impact of thousands of logs would scour the channel down to bedrock (Sedell and Luchessa 1981, Opperman et al. 2006, Harmon et al. 1986).

Legacy effects of destructive forestry practices. (top) Splash dams were used to transport logs during low flows or in smaller channels. (middle) Repeated log drives and log jams scraped away at the banks and streambed. (bottom) Instream roads and skids "paved over" the streambed.

In California, forested riparian areas are now regulated under the California Forest Practice Rules (1974) which require management of riparian zone to provide shade, protect streambanks, and provide habitat. Buffers are usually established around streams where harvest is either limited to selective thinning or prohibited outright as part of a timber harvest plan (THP). This allows trees to mature and contribute to future supplies of in-stream wood.

1.3.3 Stream Improvements for Fish

Wood removal also occurred out of misguided notions about suitable fish passage and habitat. For a time, “stream cleaning” was synonymous with “stream improvements” for fish. An influential bulletin published by CDFG (Shapovalov and Taft 1954) recommended removal of log jams and debris clogging stream channels to improve quality of, and access to spawning habitat. In the 1980s, two bills (Energy Resources Fund [1980] and the Bosco-Keene AB951 [1981]) were passed which allocated $1 million annually for salmon restoration (Wooster and Hilton 2004). As part of the salmonid restoration plan, streams were to be cleaned at the rate of at least 100 miles per year (California Resources Agency 1982) and early efforts often stripped streams of all wood below the high water mark (Wooster and Hilton 2004).

Stream cleaning activities are still conducted as part of forest management activities to prevent logging slash from clogging streams after harvest and blocking upstream migrating salmonids (Bisson et al. 1987). However, scientists who study fish movement and wood accumulations have found that naturally occurring jams are rarely barriers to fish (Opperman et al. 2006). Many researchers have since documented the deleterious effects of wood removal on aquatic habitats, and by the late 1980s the stream restoration paradigm already began shifting towards selectively removing debris jams, while strategically replacing large wood as in-stream structures.

The listing of coho salmon (Federally Endangered) and steelhead (Federally Threatened) in the mid- to late-1990s focused even more attention on the role of large wood in providing habitat for all life stages. Today, most fisheries biologists agree that large wood plays a key role as a structural element in establishing and maintaining pools and providing unique stream features. Although no longer practiced on the same scale as before, wood removal is still a large part of salmon enhancement programs in several western states, and it is mandated by nearly all forest practice acts in the western United States and Canada (Bisson et al. 1987).

1.3.4 Continued Removal—Aesthetics, Safety, and Infrastructure Concerns

The important role that large wood plays in forested streams is now widely accepted (Sedell et al. 1982, Bisson et al. 1987); however, large wood is still regularly removed by landowners and agencies (Lassettre and Kondolf 2011, Dolloff 1986). Agencies conducting channel maintenance projects regularly remove or significantly alter large wood to improve channel capacity and reduce the threat of flooding and erosion from logjams.

Although within California, it is illegal to remove large wood from creeks without contacting the Department of Fish and Game (CDFG) or another designated agency for consultation, a lot of wood is removed from streams in error. As Dolloff (1994) points out, *"The term 'stream improvement,' at one time used by loggers and rivermen to mean removal of any hindrance to free flow, including LWD and large rocks or boulders, now has exactly the opposite meaning."* Landowners still remove wood especially if it appears to threaten lives or property, and despite the proven value of large wood to fish many good Samaritans still view large wood as a barrier to fish passage and remove wood to help the fish. Wood removal may also be driven by aesthetic preferences. In an assessment of visual preference for rivers in woodland areas, the general preference was for channels that did not have in-channel debris (Gregory and Davis 1993, Piégay et al. 2005).

In-stream wood can also create hazardous conditions for recreational boaters. Common boater terminology for in-stream wood, such as "sweeper" (a tree that has fallen over a river with branches extending into the water that may "sweep" a person off their boat), or "strainer (a feature that allows water to pass but blocks solids, such as a capsized boater) hint at the highly antagonistic relationship. The connection between boater safety and in-stream wood is probably best captured in this quote:

> "*Logs are the predators of paddlers and we treat them how our ancestors in this country treated wolves and mountain lions. They are generally disliked, their importance to the ecosystem is completely misunderstood, they are removed whenever possible, and if one is ever implicated in the injury or death of a human it is ceremoniously destroyed."*
>
> --Kevin Colburn "How Much Wood Does a Paddler Chuck?"
> American Whitewater Journal Mar/Apr 2001

Occasionally, a fallen tree will threaten infrastructure or cause significant bank erosion. In such cases, wood removal is warranted to protect loss of life and/or property, but still requires consultation by an agency.

1.4 Removal is Bad: Disrupting the Wood Regime Unravels the System

1.4.1 Unhinging the Wood Regime

Wood removal and harvest in the riparian zone disrupts the wood regime and affects the distribution and abundance of large wood in streams for years to come (Hicks et al. 1991) (Figure 1-3). Direct removal of wood from rivers affects the standing stock of in-stream wood and eliminates direct in-channel benefits (present). Removal of streamside timber in the riparian zone reduces the rate at which new pieces can be contributed to the stream (future). Regular cycles of harvest decrease the size of wood pieces that can be recruited (quality) (Andrus et al. 1988, Bilby and Ward 1991, Ralph et al. 1994). The overall result is fewer large, stable pieces in streams of all sizes, pieces concentrated in large but infrequent accumulations, and diminished sources of future woody material for stream channels (Bisson et al. 1987).

Studies of streams in harvested areas found that diameters of in-stream wood and wood loading in harvested (second-growth) sites were lower when compared than in old-growth areas (Benda et al. 2002, Silsbee and Larson 1983, Flebbe and Dolloff 1991, Maahs and Barber 2001). Some researchers estimate that trees must grow longer than 50 years to ensure that a sufficiently-sized, long-term supply of woody debris is available for stream channels (Andrus et al. 1988).

1.4.2 Unraveling Habitat

Removing wood disrupts not only the wood regime but the hydro-geomorphic and biological processes that have adapted to it (Mellina and Hinch 2009). There is generally a long-term reduction in stream-bank stability, and retention of organic matter that leads to elevated suspended sediment levels (Gregory et al. 1987, Andrus et al. 1988, Fausch and Northcote 1992). Clearing streams of large wood reduces stream habitat diversity and alters patterns of channel erosion and sediment transport (Boon et al. 1992). Wood-depleted streams are often characterized by simplified structure, and homogenous longitudinal profiles with fewer, shorter and shallower pools (Bilby 1984, Lisle 1986a, Lisle 1995, Ralph et al. 1994).

This loss of in-stream wood and wood-formed habitats is especially problematic for fish species that have diverse habitat needs. Furthermore, loss of streamside vegetation can affect in-stream conditions. Harvest in the riparian zone reduces canopy cover and therefore interception of rainfall and shading. Loss of canopy cover can therefore lead to elevated stream temperatures and faster delivery of water to the stream. Streams and rivers with insufficient wood loading have lower abundance, diversity, quality, and quantity of habitat.

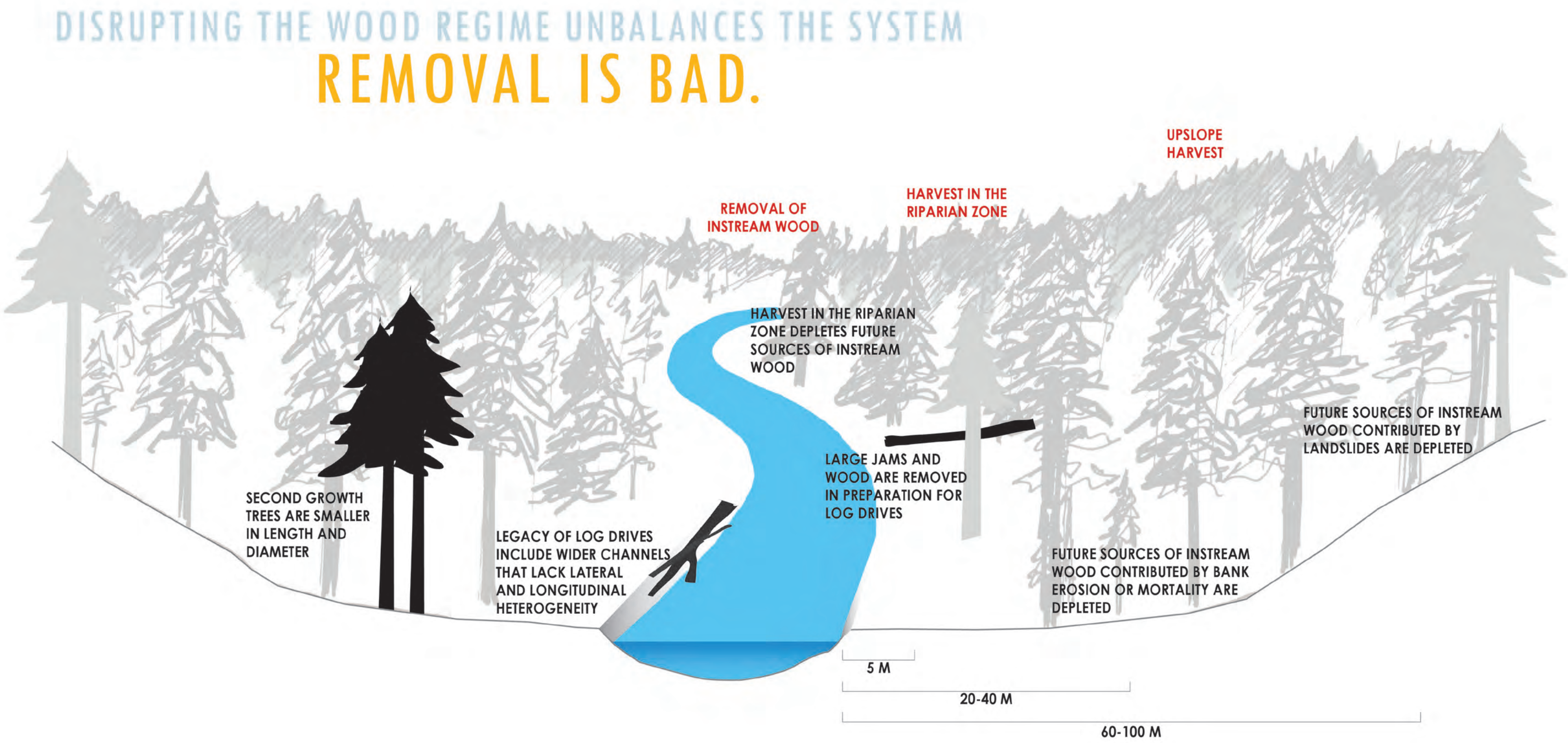


FIGURE 1-3.
Conceptual understanding of a disturbed wood regime.

1.4.3 Implications for Fish

Depletion of large in-stream wood has important consequences for fish populations. Insufficient distribution and abundance of large in-stream wood diminishes the quantity and quality of habitat, leading to greatly reduced fish density and biomass (Gregory et al. 1987, Andrus et al. 1988, Fausch and Northcote 1992). Juvenile salmonid abundance is heavily reliant on the amount of large in-stream wood (Murphy et al. 1986, Bisson et al. 1987) and even selective wood removal can decrease the carrying capacity for juvenile salmonids (Dolloff 1986, Elliott 1986). The loss of pool habitat and complexity, as well as decreased diversity and availability of refugia can lead to lower fish abundance, average size, and biomass for fish species (Dolloff 1986, Coulston and Maughn 1983, Elliott 1986, Fausch and Northcote 1992) and overall reductions in stream carrying capacity (Lestelle and Cederholm 1984, Scrivener and Brownlee 1989). Furthermore, long-term changes in species composition of fish communities, including shifts in dominance and the disappearance of formerly common species, have been linked to habitat simplification following timber harvest and subsequent decreases in residual large wood loading and input (Reeves et al. 1993).

SECTION 2

Wood Restoration Projects

2.1 Re-Placing Wood is a Short-Term but Necessary Solution

When the wood regime is severely disrupted, in-stream wood abundance can decline and remain low for years following logging. In instances where a vegetated buffer strip is retained, it can take 60–75 years for natural recruitment to recover to pre-harvest levels (Grette 1985, Andrus et al. 1988); but, recovery can take more than 250 years where streamside vegetation has been clear cut (Murphy and Koski 1989, Beechie et al. 2000).

In the interim, biological functions continue to decline in the absence of this essential element. There are concerns that declining steelhead and coho populations require immediate attention to prevent further loss and perhaps extinction. The ecological importance of large wood as an in-channel element has become widely accepted in recent decades, leading many to advocate for re-placing large wood in streams to compensate for the reductions in wood loading following decades of stream cleaning and other land use practices. However, many regard the addition of in-stream habitat enhancement structures as a

Artificial large wood structure bolted into boulders (Napa County).

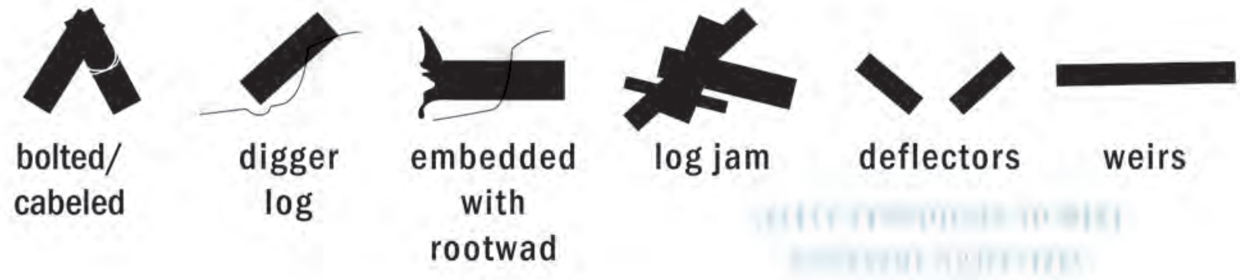


FIGURE 2-1.
Typologies of common in-stream structures used in wood restoration projects.

critical, but ultimately temporary means to remedy this situation and support fish populations in the short-term (Kail et al. 2007).

While the placement of wood and boulders in streams to restore or enhance fish habitat and increase fish numbers has been occurring in North America since at least the 1930s (Tarzwell 1934, Meehan 1991, Reeves et al. 1991), putting wood back in streams has become an increasingly popular restoration strategy in recent years (Kauffman et al. 1997). Restoration strategies include cabling or bolting wood in place, partially burying wood in streambanks, wedging pieces in place using boulders or live standing trees, or strategically placed in the channel to be a “floater” and lead to natural accumulations (Figure 2-1). Theoretically, properly placed and constructed in-stream structures should reinstate the benefits lost due to wood removal.

2.2 What have we Learned from Wood Restoration Projects?

There are many lessons to be learned from several decades of large wood restoration projects. Previously, monitoring of stream restoration projects focused primarily on assessing physical habitat responses to placed large wood, and whether structures functioned as designed. More recently, studies have been published that emphasize biotic responses. Understanding the characteristics of the structure, placement, and conditions that lead to success or failure of a project will in turn help us understand the factors that limit efficiency of wood placement as a restoration technique.

2.2.1 “Staying Power” of Artificially Placed Large Wood

The extent to which the artificially placed large wood structures remain in place and continue to function after several years is unclear (Ehlers 1976, Armantrout 1991, Frissell and Nawa 1992, Roper et al. 1998). Frissell and Nawa (1992) evaluated rates and causes of physical impairment or failure for 161 fish habitat structures in 15 streams in southwest Oregon and southwest Washington, following high flows (recurrence interval of 2–10 years). Rates of overall damage to structures ranged from 27–100% in southwest Oregon (median, 70%; mean, 67%), and 0–89% in southwest Washington (median, 42%; mean, 46%). In the second year following installation of 72 large wood structures along Little Topshaw Creek (north Central Mississippi), approximately one third of all structures were damaged by high flows (Sheilds 2003). Schmetterling and Pierce (1999) documented the resilience of wood structures following the 50-yr flood and found that 85% (n = 66) of the structures were retained.

2.2.2 Ability of Placed Wood to Alter Channel Morphology

Many authors have documented improvement in the hydro-morphological status of streams and rivers by wood additions in the form of increases in pool frequency, pool depth, woody debris and sediment retention following placement of in-stream structures (e.g., Kail et al. 2007, Anderson et al. 1984, Armantrout 1991, House et al. 1991, Crispin et al. 1993, Cederholm et al. 1997, Reeves et al. 1997). In their compilation of data from 211 stream restoration projects, Whiteway et al. (2010) showed a significant increase in pool area, average depth, large woody debris, and percent cover, as well as a decrease in riffle area, following the installation of in-stream structures.

Techniques for using placed wood in restoration are improving, and studies have shown that wood measures are most successful if they mimic natural wood. However, in many cases, restored wood quantities (number and total wood volume) are still too low overall as indicated by 1) comparisons with historical levels or its potential natural state, 2) low quantity and quality of pools and cover, or 3) the stream in general lacks hydraulic complexity (Bisson et al. 1987, Kail et al. 2007). Wood restoration projects, whether or not they mimic natural processes, are still small-scale, temporary solutions until overall natural recruitment recovers.

2.2.3 Artificially Placed Wood is Good for Biota

Wood placement can improve habitat for many fish species. Kail et al. (2007) found that wood placement had beneficial effects on fish species, and Roni (2001) found strong evidence that artificially placed large wood lead to significantly higher densities of juvenile coho in summer and higher densities of coho, cutthroat and steelhead during winter, especially in sites deficient in wood to begin with. Similarly, Whiteway et al. (2010) found that both salmonid density and biomass increased following installation of instream wood structures.

Additions of large wood can benefit macroinvertebrates as well. In a meta-analysis of in-stream restoration projects, Miller et al. (2010) observed a significant positive relationship between habitat heterogeneity and macroinvertebrate richness, with large wood additions producing the largest and most consistent responses. In contrast, boulder additions and channel reconfigurations produced highly variable responses.

While there has been significant progress on understanding the response of fish populations to wood placement, to date, there have been very few attempts to manipulate and link specific amounts of large in-stream wood to fish production.

2.2.4 Position in the Landscape: Sources of Variability

As is the case with natural wood, channel response to placed large wood is highly variable and the potential sources of variation are vast, difficult to pinpoint, and likely interact in ways that are not fully understood. Most studies are limited to analyzing 1-to-1 relationships of dependent and independent variables, but a few studies have ventured out to understand relative importance and influence of multiple factors.

As an example, Roni (2001) conducted a multiple regression analysis that indicated that physical variables (e.g., pool depth, cover, large woody debris, etc.) explained 10% or less of the variation in fish densities among pools, while reach-scale physical variables (e.g., elevation, drainage area, precipitation, stream gradient, percent pool area) explained from 22% to 63% of the variation of species density among streams. This suggests that reach-scale physical variables may be better predictors of fish densities among streams than variables measured within individual habitat units.

Furthermore, in their review of rehabilitation projects Roni et al. (2008) demonstrate that failure to achieve objectives was attributable to inadequate assessment of historic conditions and factors limiting biotic production; poor understanding of watershed-scale processes that influence localized projects; and monitoring at inappropriate spatial and temporal scales.

Scale and context are often cited as necessary for fully understanding how large wood placement fits in the system. Frissell and Nawa (1992) noticed a high degree of variability amongst streams suggesting that *"…complex, multi-scale interactions between watershed conditions, fluvial processes, and structure design determine the physical success or failure of individual structures and projects."* Their study suggests that direct structural modifications of channels, such as large wood placement, are unlikely to succeed unless these larger-scale issues are dealt with first.

The restoration context and natural disturbance regimes of streams and rivers, including the geomorphic setting of the channel, are required to make informed decisions (Elosegi and Johnson 2003). Abbe et al. (2003) state that it is important to consider watershed and reach-scale context when using wood for river rehabilitation and management, a sentiment echoed by many researchers (e.g., Kail et al. 2007, Beechie and Sibley 1987). Despite the wide recognition of the need to consider scale and context, few researchers have actively acted to address this deficiency.

2.3 Monitoring: Success? Failure? How can you tell?

Approximately $1 billion is spent on river restoration each year (Bernhardt et al. 2005). Understanding the effectiveness of various habitat rehabilitation techniques is critical for project planning, directing future restoration efforts, and project design (Roni 2005). Unfortunately, little research and monitoring have occurred to determine the effectiveness of these and other restoration efforts (Reeves et al. 1991, Kondolf 1995, Kauffman et al. 1997).

Bernhardt et al. (2005) found that only 10% of project records indicated that any form of assessment or monitoring occurred, while Kail et al. (2007) found that monitoring was conducted in only 58% of wood restoration projects in Germany and Austria. In a survey of more than 4,000 projects in the California summary database, only 22% reported having a monitoring component (higher than the average of 10% for the national database) (Bernhardt et al. 2007, Kondolf et al. 2007).

2.3.1 Success Criteria

Few restoration projects have sufficient pre-project baseline monitoring data against which to develop success criteria and evaluate project outcomes. In numerous interviews with restoration practitioners, Bernhardt et al. (2007) found that post-project appearance and positive public opinion were the most commonly used metrics of success. Without critical evaluation, restoration science cannot learn from our past collective experience, perpetuating restoration projects that lack the evidence needed to justify habitat manipulations (Palmer 2009, Kondolf et al. 2007). This situation is unlikely to change without incentives for practitioners to evaluate and report project outcomes. Palmer et al. (2005) suggests that well-accepted success criteria and standards for evaluation (that are ultimately supported by funding agencies) would promote ecologically-sound and more effective restoration efforts.

2.3.2 Monitoring that is Limited in Scope: Temporal and Spatial Considerations

Researchers widely acknowledge the need for long-term monitoring and the need to relate unit- or reach-scale results in the context of the overall watershed (e.g., Miller et al. 2010, Wooster and Hilton 2004). Kondolf (1995) recommends monitoring projects for at least 10 years to allow physical and biological changes to manifest, or to adequately capture project response to perturbations (e.g., flood events). However, few projects have long-term post-implementation monitoring to thoroughly evaluate whether a project meets its intended goals and objectives. Furthermore, effectiveness monitoring of emplaced wood often occurs over very small temporal and/or spatial scales. Whiteway et al. (2010) acknowledged the scarcity of long-term monitoring of the effectiveness of in-stream structures as limiting and “problematic.”

2.3.3 Funding and Failure

Many researchers have noted that few restoration projects are described in open literature (Kail et al. 2007, Kondolf 1995, Palmer 2009) with a tendency for only publishing results from “successful” projects. Kondolf (1995) recognized the stigma associated with managing or designing a “failed” project, but the learning process is essential for improving the knowledge base for scientists and practitioners. Furthermore, it is difficult to secure funding for monitoring projects due to their intangible nature and ambiguity in producing direct benefits. In some cases, monitoring projects fall under the category of “research” which is ineligible for certain funding sources.

2.3.4 Status of Monitoring for Large Wood Projects

Specifically related to wood restoration projects, overall, very few analyses have been done which examine the 1) long-term wood-induced changes in channel morphology to 2) strategize placement of wood for restoration purposes, 3) in relation to the overall watershed context. Temporally and spatially appropriate monitoring data are needed to learn from past experience and improve future project design. Even fewer analyses have been done which systematically examine the independent physical factors which may be influencing the variability in wood performance. The lack of systematic, objective assessments of completed projects hinders the advance of restoration science (Kondolf et al. 2007). Temporally and spatially appropriate monitoring data are needed to learn from past experience and improve future project design (Kondolf 1998, Kondolf 1995, Palmer 2009).

SECTION 3

The Gualala River Watershed

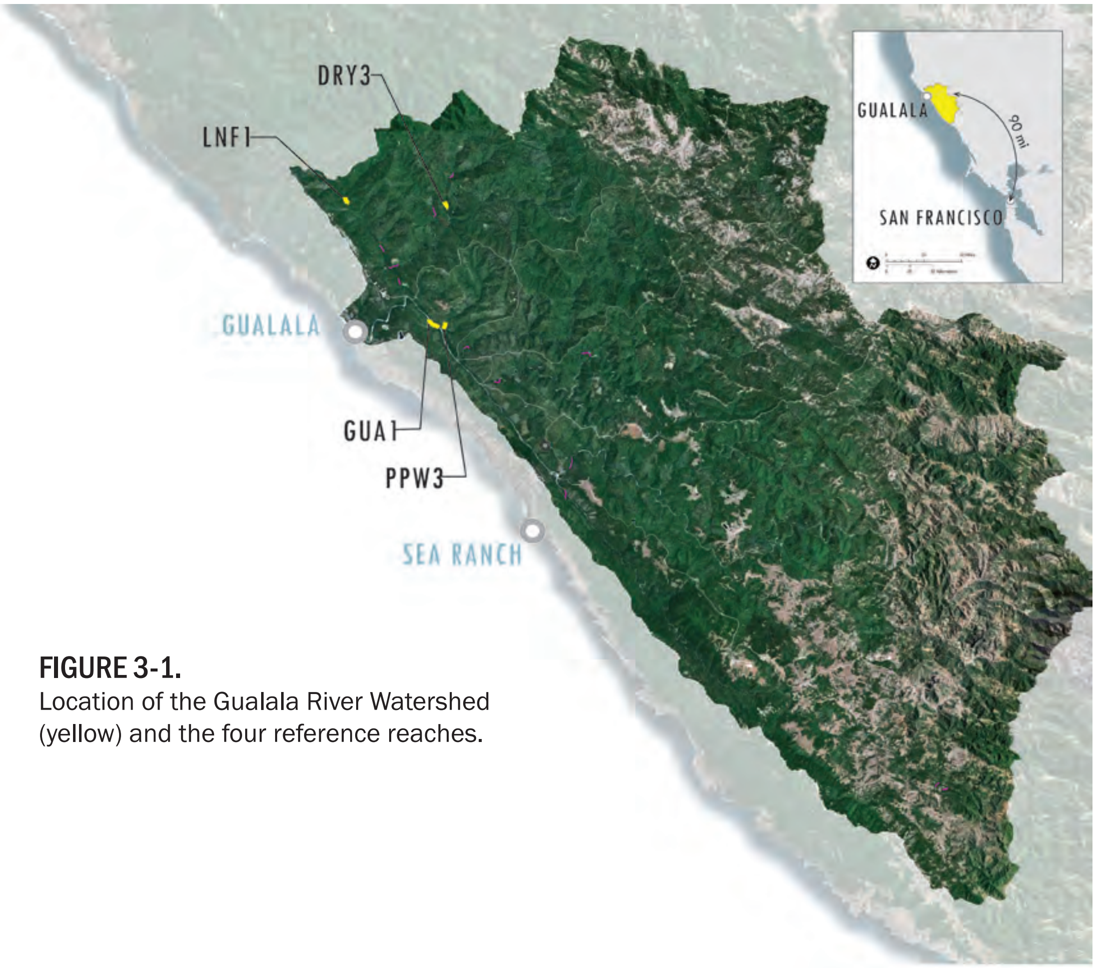


FIGURE 3-1.
Location of the Gualala River Watershed (yellow) and the four reference reaches.

The Gualala River Watershed (298 mi^2) is located in northern California, straddling both Mendocino and Sonoma Counties (Figure 3-1). The Gualala River spills out of the northern California Coastal Ranges finally entering the Pacific Ocean at the town of Gualala, 90 miles north of San Francisco and 17 miles south of Point Arena.

The watershed has a rural population of 3,419 centered near four unincorporated communities: Gualala, Sea Ranch, Annapolis and Stewarts Point. The Gualala River Watershed, the largest watershed in the Mendocino Coast Hydrological Unit, is divided into five major subbasins (Table 3-1, Figure 3-2).

TABLE 3-1.
Characteristics of the five major Gualala River Watershed subbasins.*

	Wheatfield	South Fork	North Fork	Buckeye	Rockpile
Area (mi^2)	47.9	35	39.9	111.6	63.7
% of total drainage area	37%	21%	16%	14%	12%
Length of blue line stream (mi)	127	88	90	246	134

*Table reproduced from Table 3-1 (Klamt et al. 2003).

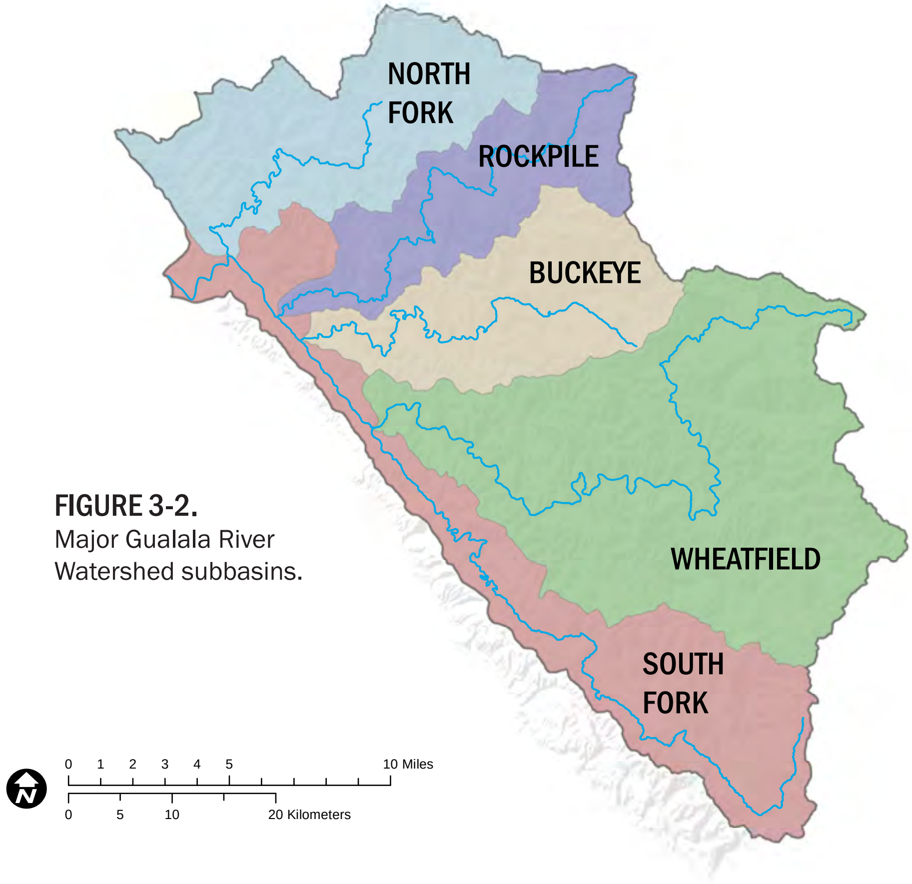


FIGURE 3-2.
Major Gualala River Watershed subbasins.

Historically active landslides cover approximately 9% of the total watershed area (Klamt et al. 2003). The majority of the watershed is dominated by coastal conifer forests (redwood and Douglas fir), with the interior dominated by oak-woodland and grassland (Figure 3-3) (Klamt et al. 2003). The watershed has a long history of destructive timber harvest practices that included splash damming, and instream roads and skids (Figure 3-4). The majority of the watershed is privately-owned by timber companies with active harvest operations in the watershed (Figure 3-5). Past and present timber harvest operations have resulted in an extensive network of roads and trails (Figure 3-6), and left a legacy of conditions that impair habitat for coho and steelhead salmon.

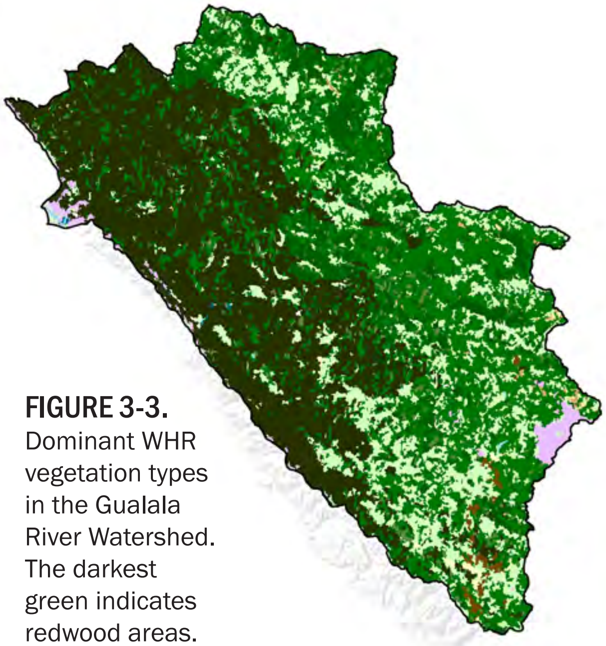


FIGURE 3-3.
Dominant WHR vegetation types in the Gualala River Watershed. The darkest green indicates redwood areas.

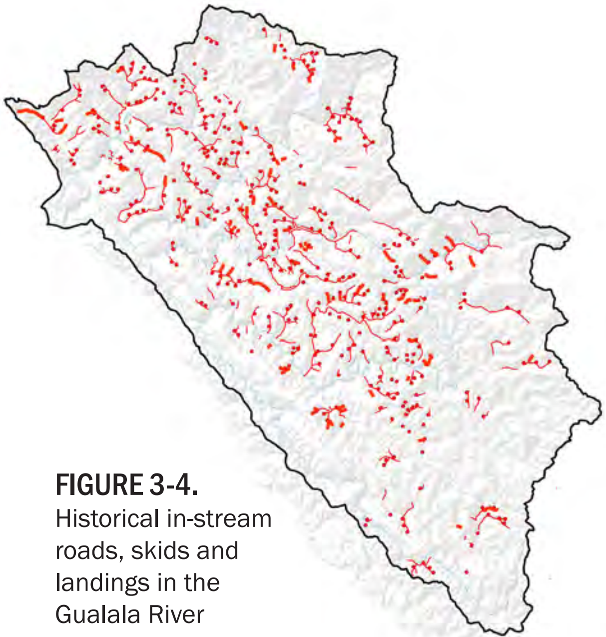


FIGURE 3-4.
Historical in-stream roads, skids and landings in the Gualala River Watershed.

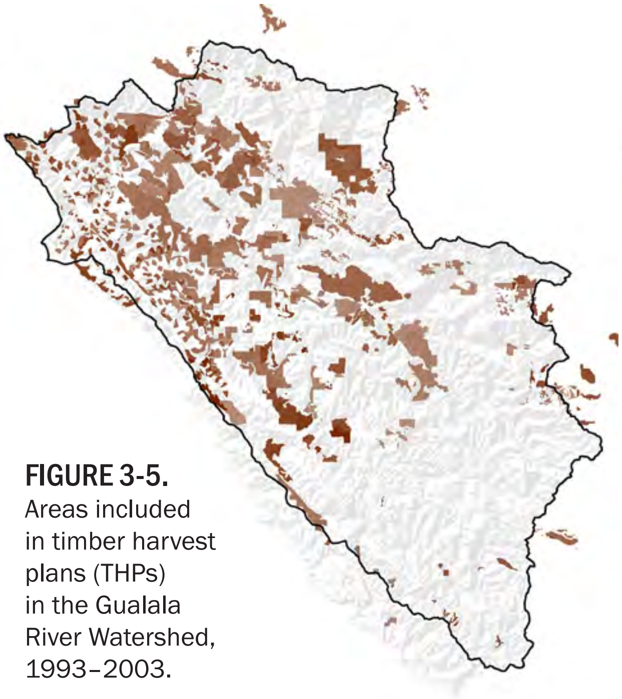


FIGURE 3-5.
Areas included in timber harvest plans (THPs) in the Gualala River Watershed, 1993–2003.

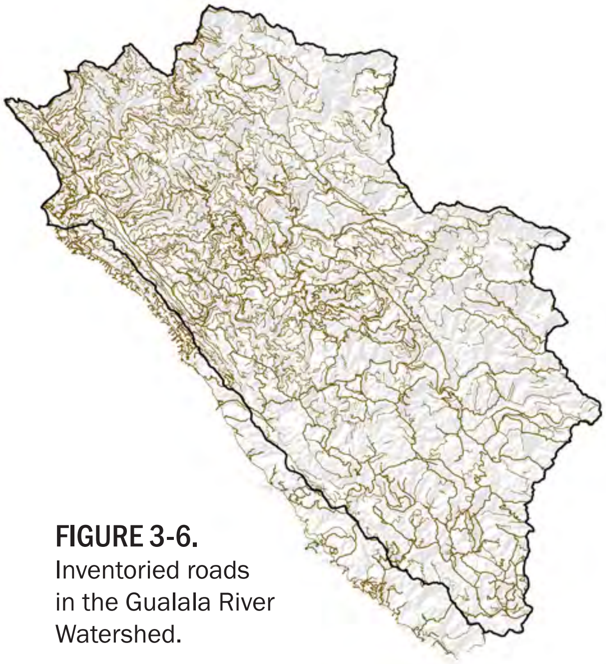


FIGURE 3-6.
Inventoried roads in the Gualala River Watershed.

3.1 Historical Context

3.1.1 Logging History

The area has long depended on timber and agriculture as a main source of employment with 80% of all the watershed lands zoned for timber production (Klamt et al. 2003). The Gualala River watershed has one of the longest histories of timber harvested in the North Coast of California (Figure 3-7). Logging of the virgin old growth redwood forest began during the mid-1800s with the first documented harvest occurring in 1862 in lower portions of the watershed near coastal ramp and port facilities includes the lower reaches of the Little North Fork, North Fork, Pepperwood creeks, and the lowest reaches of Rockpile and Buckeye creeks at the confluence with the South Fork (Morse 2002).

Extensive logging and associated road building practices in this fragile and highly erosive landscape contributed to erosion and mass wasting, producing a legacy of elevated sediment loads and severely impacting aquatic habitat throughout the watershed. The mainstem Gualala River was used to float logs downstream to the mills and railroads on the coast. Watercourses were frequently used as skid paths

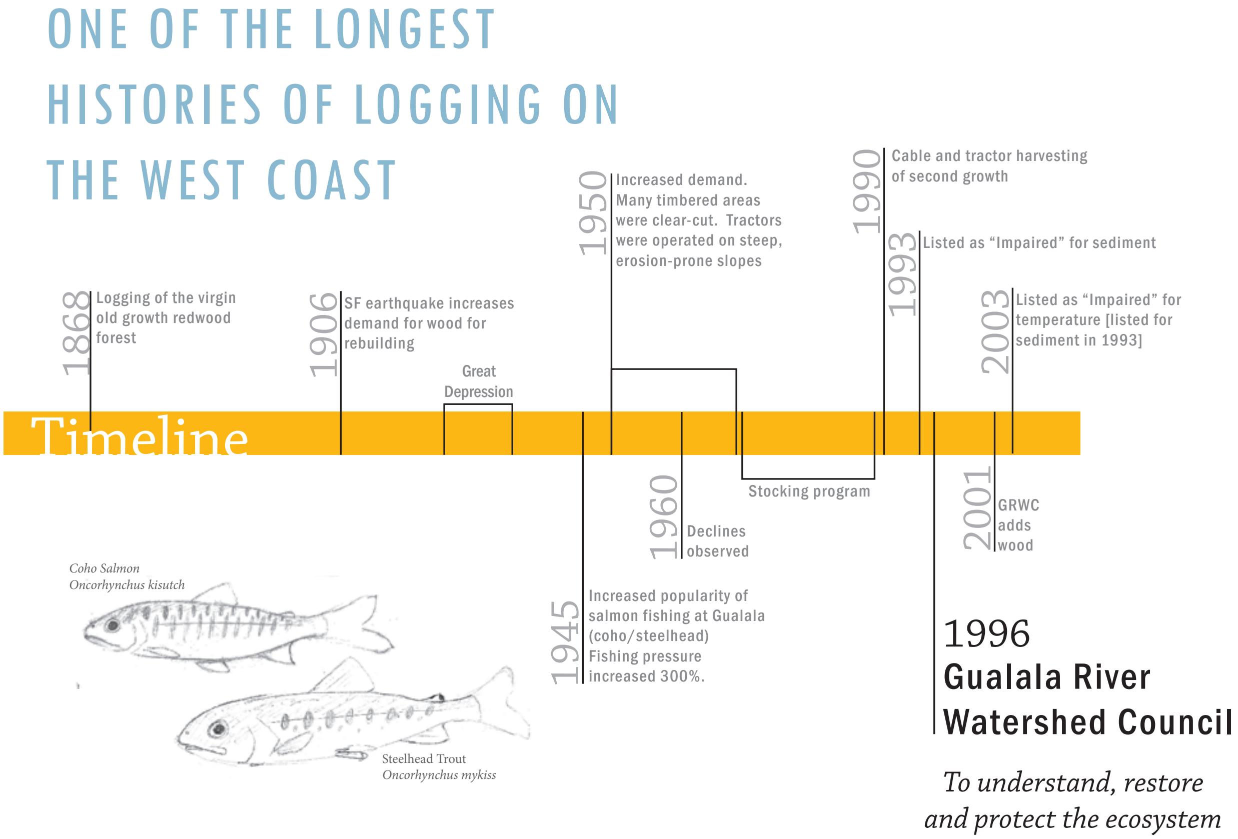


FIGURE 3-7.
Timeline of notable timber harvest and fisheries events.

to move logs downslope, and splash damming was a common practice (Morse 2002). Historical logging practices left a legacy of flattened and simplified stream channels from repeated log drives, stream beds that were filled in for rail line and road construction.

Historical logging operations impaired watercourses, however more recent tractor operations (characterized by large-scale sideslope excavations and skid trail networks) disturbed the ground to a greater extent and continue to contribute excessive amounts of sediment to streams throughout the watershed (Morse 2002).

Floods in the north coast region of California in 1955 and 1964, combined with intensive logging, delivered large volumes of wood to streams (Wooster and Hilton 2004). In 1964, the California Department of Fish and Game (CDFG) listed several recommendations based on stream surveys conducted throughout the watershed. As a result, logging debris, log jams, and other woody materials were cleaned (cleared) from streams by CDFG and the California Conservation Corps throughout the watershed in the 1970s and 1980s (LeDoux-Bloom 2002).

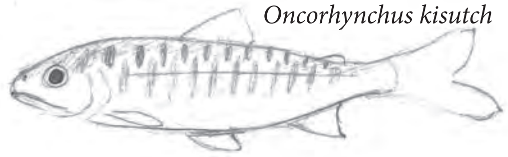
Historical photos of the deforestation and in-stream modifications imposed by timber harvest operations in the Gualala River Watershed. (top) Railroad landing and "steam donkey" circa 1902. (bottom) Logging crew circa 1905 and a streambed near the upper center paved with log sections. Photos provided courtesy of the Mendocino Historical Society and the Held Poage Memorial Home and Research Library.

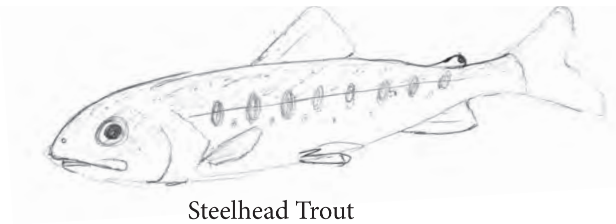
3.1.2 Impacts to Fisheries

Coho and steelhead were historically abundant in the Gualala River watershed (LeDoux-Bloom 2002) (Figure 3-8). Coho salmon naturally inhabited the streams flowing from coniferous forests, but likely were sub-dominant to steelhead trout in interior areas due to the more open nature of the channels, less suitable habitat, and naturally warmer stream temperatures (the interior is largely grassland with scattered oaks).

FIGURE 3-8. Historical coho bearing streams in the Gualala River Watershed.

Coho Salmon
Oncorhynchus kisutch





Steelhead Trout
Oncorhynchus mykiss

Starting in the 1940s and continuing today, steelhead have been recreationally fished on the Gualala River (LeDoux-Bloom 2002). In 1945, fishing pressure is thought to have increased by 300% due to increased popularity of salmon fishing on the Gualala River (LeDoux-Bloom 2002). The mid-1950s to the mid-1960s were marked by intensive tractor logging causing extensive damage to the streams and headwaters of the Gualala River (Morse 2002). The resulting logging debris and log jams created fish passage barriers, affected habitat quality, and limited access to suitable habitat for steelhead trout in the Gualala River Watershed (Morse 2002). Declines in populations of both species were observed in 1960, prompting CDFG stream surveys in 1964. The outcome of the 1964 surveys were a set of management recommendations that included 1) extensive stream clearing by CDFG and the California Conservation Corps throughout the Gualala River Watershed to improve fish habitat, and 2) initiating a coho stocking program (LeDoux-Bloom 2002). Thirty years of extensive planting of coho followed in an attempt to reestablish a viable self-supporting run in streams with pre-existing populations. CDFG began planting coho in 1969 and steelhead trout in 1970. From 1969 to 1999, 347,780 hatchery coho salmon were stocked. Between 1972 and 1990, a total of 444,530 steelhead trout were planted.

In 2001, over 100 miles of habitat inventory surveys were conducted on 18 streams. The Coho Salmon Status Report (CDFG 2002) found coho salmon absent from their historical streams and stated there were no known remaining viable coho salmon populations in the Gualala River system. In September 2002, a few coho salmon young-of-the-year were observed in tributaries of the North Fork subbasin.

According to NOAA and CDFG only three planning watersheds in the Gualala River Watershed still have habitat for the California Central Coast (CCC) coho—Doty and Robinson creeks (in the North Fork Gualala), and Pepperwood Creek in the lower South Fork, whereas steelhead salmon distribution in the Gualala River Watershed does not appear to have changed over the past 37 years. In 2002, CDFG concluded that CCC coho salmon were in serious danger of extinction throughout all or a significant portion of their range (CDFG 2002).

3.2 Current Setting

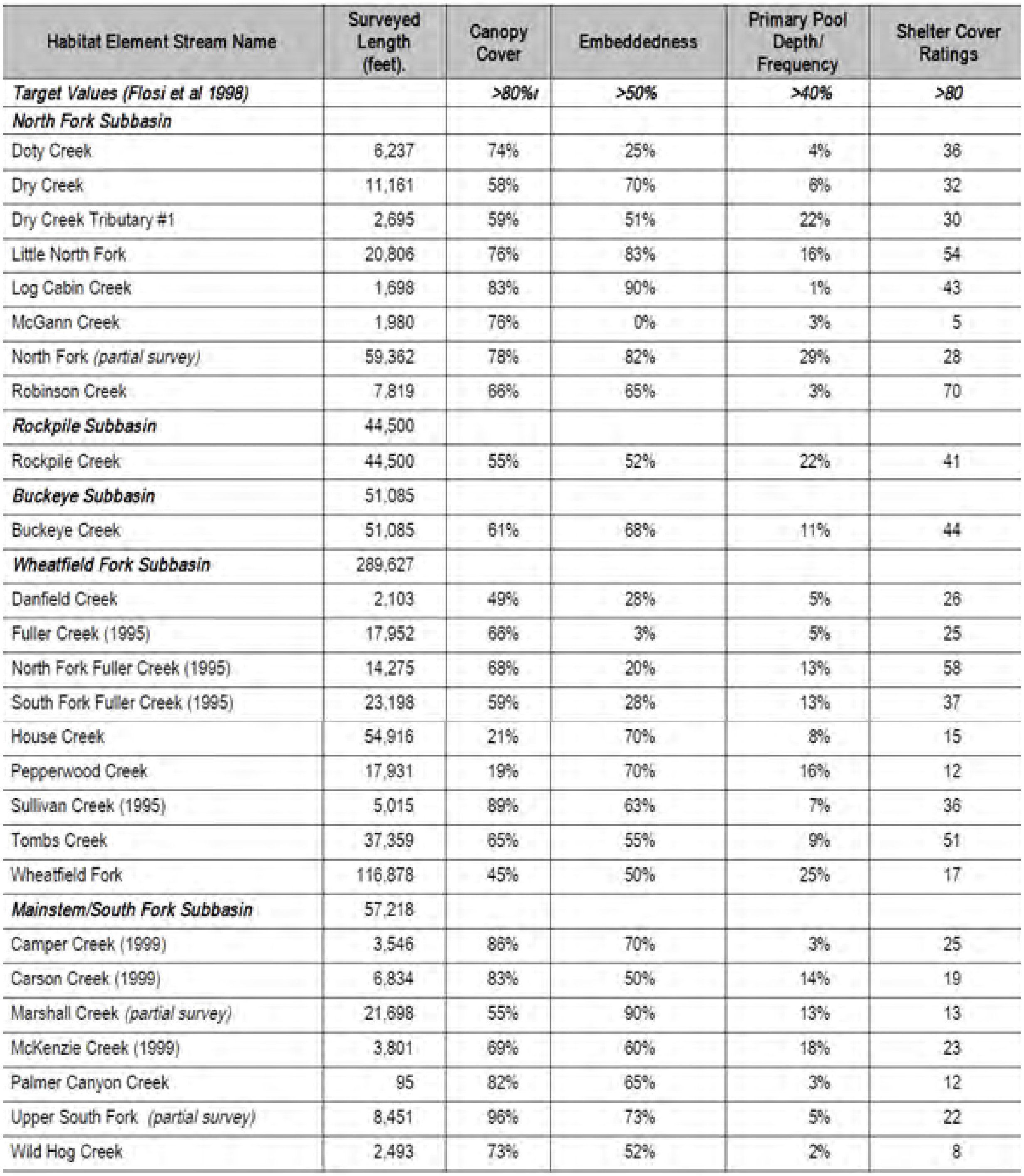
Large scale block clear-cutting projects in the 1950s and early 1960s eliminated over-story shade canopy from primary streams that had provided spawning grounds for anadromous salmonids. The removal of coniferous species in the riparian corridors resulted in a lack of mature riparian for wood recruitment, and a lack of deep pools with shelter needed for salmon and steelhead summer rearing habitat.

In 1993, the Gualala River was listed as impaired by the U.S. EPA under federal Clean Water Act §303(d) due to declines in anadromous salmonids attributed to excessive sedimentation. In 2003, the impairment listing was updated to include water temperature impairment as well. A 2003 Technical Support Document prepared as part of the Gualala River Watershed's TMDL process, estimated that 85% of the anthropogenic sediment sources impacting the river today are derived from poorly constructed timber and ranch roads.

The 2002 Limiting Factors Analysis (LFA) conducted by CDFG for the Gualala River identified several factors limiting salmonid health and production. In the Gualala River Watershed as a whole, and particularly in the North Fork, Wheatfield and Mainstem/South Fork subbasins, "Pool Shelter Related to Escape and Cover" was identified as limiting, while "Pool Depths Related to Summer Conditions" was identified as the primary limiting factor the Rockpile and Buckeye subbasins.

Little North Fork Creek,
Gualala River Watershed

TABLE 3-2.
Summary of current (1995, 1997, and 2001) stream conditions based on habitat inventory surveys from the Gualala River Watershed.*



Habitat Element Stream Name	Surveyed Length (feet).	Canopy Cover	Embeddedness	Primary Pool Depth/ Frequency	Shelter Cover Ratings
Target Values (Flosi et al 1998)		*>80%i*	*>50%*	*>40%*	*>80*
North Fork Subbasin					
Doty Creek	6,237	74%	25%	4%	36
Dry Creek	11,161	58%	70%	6%	32
Dry Creek Tributary #1	2,695	59%	51%	22%	30
Little North Fork	20,806	76%	83%	16%	54
Log Cabin Creek	1,698	83%	90%	1%	43
McGann Creek	1,980	76%	0%	3%	5
North Fork *(partial survey)*	59,362	78%	82%	29%	28
Robinson Creek	7,819	66%	65%	3%	70
Rockpile Subbasin	44,500				
Rockpile Creek	44,500	55%	52%	22%	41
Buckeye Subbasin	51,085				
Buckeye Creek	51,085	61%	68%	11%	44
Wheatfield Fork Subbasin	289,627				
Danfield Creek	2,103	49%	28%	5%	26
Fuller Creek (1995)	17,952	66%	3%	5%	25
North Fork Fuller Creek (1995)	14,275	68%	20%	13%	58
South Fork Fuller Creek (1995)	23,198	59%	28%	13%	37
House Creek	54,916	21%	70%	8%	15
Pepperwood Creek	17,931	19%	70%	16%	12
Sullivan Creek (1995)	5,015	89%	63%	7%	36
Tombs Creek	37,359	65%	55%	9%	51
Wheatfield Fork	116,878	45%	50%	25%	17
Mainstem/South Fork Subbasin	57,218				
Camper Creek (1999)	3,546	86%	70%	3%	25
Carson Creek (1999)	6,834	83%	50%	14%	19
Marshall Creek *(partial survey)*	21,698	55%	90%	13%	13
McKenzie Creek (1999)	3,801	69%	60%	18%	23
Palmer Canyon Creek	95	82%	65%	3%	12
Upper South Fork *(partial survey)*	8,451	96%	73%	5%	22
Wild Hog Creek	2,493	73%	52%	2%	8

*Table 10 in LeDoux-Bloom (2002).
** Habitat Inventory Target Values are taken from the California Salmonid Stream Habitat Restoration Manual (Flosi et al. 1998).
*** LeDoux-Bloom (2002) explains the target value for embeddedness as "50 percent or greater of the pool tails sampled are 50 percent or less embedded," thus providing good spawning substrate conditions.

3.3 Gualala River Watershed Council

Declines in salmonid populations motivated local citizens to work to restore populations in the Gualala River Watershed to self-sustaining levels. In the 1990s, a local coalition of restoration organizations, environmental groups, stakeholders and State and Federal Agencies was created to respond to the Clean Water Act §303(d) listing of the Gualala as an impaired waterbody. In 1996, the Gualala River Watershed Council was formed from this coalition.

The Gualala River Watershed Council (GRWC) has been monitoring the locations and conditions of large wood and the surrounding channel morphology throughout their watershed since 1998.

3.3.1 The Gualala River Watershed Monitoring Program

The Gualala River Watershed Monitoring Program was designed to examine and understand watershed conditions through the collaboration of private landowners, community groups and public agencies. Since 1998, GRWC has installed 37 monitoring reaches distributed throughout the watershed (Figure 3-9).

FIGURE 3-9. Location of current (pink) and future (purple) GRWC monitoring reaches in the Gualala River Watershed.

Four reaches have been designated as "reference reaches" and are surveyed on an annual basis (Table 3-3). All other reaches are re-surveyed on a rotational basis. Over the next decade the GRWC will install an additional 35 monitoring sites (for a total of 70 throughout the watershed).

At each monitoring reach, the GRWC surveys thalweg elevations, cross-section elevations, and in-stream large wood abundance (Figure 3-10), in addition to collecting data on riparian vegetation, canopy density, substrate size and composition, water and air temperature.

TABLE 3-3.
Periods of monitoring for each GRWC monitoring reach.

		1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
BUCKEYE CR	BUC1	▨													
	BUC3			▨								▨			
	BUC4									▨					
	BUC8								▨						
	BUC9								▨						
CARSON CR	CAR1							▨							
DRY CR	DRY2			▨								▨			
	DRY3	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
FLAT RIDGE CR	FLR2								▨						
FRANCHINI CR	FRN1									▨					
GRASSHOPPER	GRS1									▨					
JENNER G	JEN1	▨													
LNF GUALALA	LNF1	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
	LNF3				▨			▨							
MCKENZIE	MCK1							▨							
NF BUCKEYE	NFB2								▨						
NF GUALALA	NFG3		▨		▨						▨	▨			
	NFG4				▨										
	NFG5												▨		
BIG PEPPERWOOD	PPW3	🟨	🟨			🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
REDWOOD CR	RDW1									▨					
ROBINSON E	RBN1							▨					▨		
	RBN2												▨		
ROBINSON W	ROB2		▨												▨
ROCKPILE CR	ROC1									▨					
	ROC3	▨	▨				▨								
	ROC4									▨					
RUSSIAN G	RUG1			▨											
SALAL CR	SAL1			▨											
SCHOOL HOUSE	SCH			▨											
SF FULLER	SFU1								▨						
SF GUALALA	GUA1	🟨		🟨	🟨	🟨	🟨	🟨		🟨	🟨	🟨	🟨		
	SFG		▨									▨			
SODA SPRINGS	SSP1								▨						
WHEATFIELD	WFG3			▨			▨					▨			
	WFG6									▨					
	WFG7									▨					

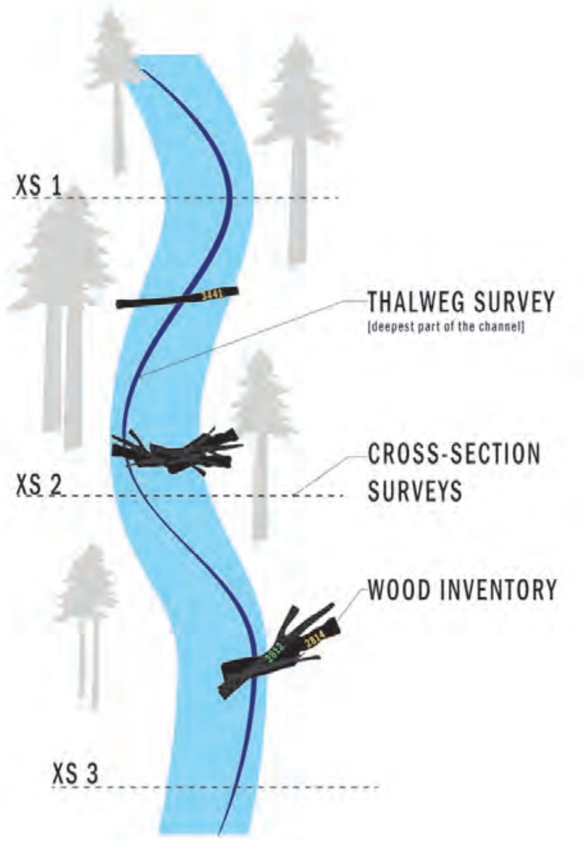
4
LONGTERM
MONITORING
REACHES

In addition to the thalweg surveys, GRWC also conduct large wood inventories. All large wood pieces (>6 in diameter, >4 ft long) are measured, assigned a unique identifier (spray painted in large orange numbers), and inventoried in an Access database. To date over 1,400 pieces are tracked in the database.

In 2001, GRWC began installing large wood to create habitat heterogeneity, impound sediment, and provide shelter for salmonids (Figure 3-11). To date, 532 pieces have been added, primarily in the Little North Fork subbasin (Table 3-4). Similar to the large wood inventory process described for the monitoring reaches, placed or "project" wood are measured, assigned a unique identifier (spray painted in large green numbers), and inventoried in an Access database.

The monitoring program was born out of a need for trend data for the entire watershed as a baseline for understanding changes in the watershed and to evaluate the progress of restoration practices (K. Morgan, GRWC Executive Director, pers. comm. 2012). At the time the GRWC was initiated, the process

FIGURE 3-10.
Schematic of GRWC's monitoring program which includes thalweg and cross-section surveys, as well as wood inventory.



ID:	#4330
Installed:	n/a
Type:	Log Jam
Species:	Red Alder
Diameter:	12 in
Length:	12 ft

ID:	#2904
Installed:	4/10/2001
Type:	Keyed
Species:	Redwood
Diameter:	31 in
Length:	41 ft

Large wood accumulation cause by wood pieces introduced by the GRWC (orange numbering) as well as naturally recruited wood (green numbering) [left bank looking toward right bank].

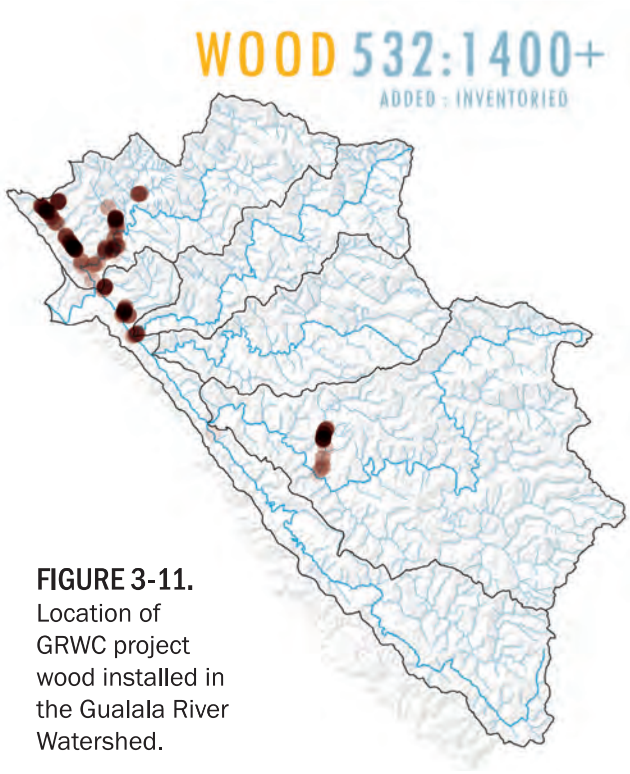


FIGURE 3-11. Location of GRWC project wood installed in the Gualala River Watershed.

TABLE 3-4. Number of pieces of project wood installed in each stream.

STREAM NAME	# of PIECES ADDED
Big Pepperwood	50
Doty Creek	24
Dry Creek	14
Fuller Creek	83
Groshong Gulch	24
Little North Fork Gualala	178
Little Pepperwood	22
North Fork Gualala	63
Robinson Cr West	52
Rockpile Creek	21
South Fork Gualala River	1
TOTAL	**532**

of mimicking natural processes and using wood for restoration were relatively new ideas. Despite demonstrated success in the nearby Jackson State Demonstration Forest (JDSF), agencies were used to highly engineered restoration techniques and hesitant to use alternative methods that would “move around” and potentially cause erosion (K. Morgan, GRWC Executive Director, pers. comm. 2012). In their first year, GRWC was experimenting with different techniques for introducing wood into streams and required monitoring data to assess the effectiveness of each technique. Having robust, quantitative data was essential to getting buy-in from skeptical landowners, wary of short-term, subjective, monitoring projects by agencies that produced no results (K. Morgan, GRWC Executive Director, pers. comm. 2012). The majority of the work by the GRWC is only possible because of matching funds by local landowners. In addition, the long-term dataset is a demonstrate record of accomplishment that has enable GRWC to get grants from agencies to continue monitoring.

Not only is the GRWC a monitoring success story, the monitoring data generated by this program represent a highly valuable long-term baseline dataset to evaluate the performance of large wood in streams, and to understand wood-pool relationships in the watershed to help guide future placement of large wood in the watershed.

SECTION 4

Thesis

The Gualala River Watershed Council's long-term monitoring database is a valuable opportunity to assess how the Gualala River Watershed is healing from a legacy of destructive forestry practices, and adapting to current conditions. In addition, the database is an opportunity to test the underlying assumption that more wood necessarily implies more pools.

The primary objectives of this study were to:

1. characterize changes in the watershed over time with respect to wood and pools,
2. test the assumption that increases in wood are correlated with increases in pool habitat, and
3. assess whether reach-specific qualities may explain the observed variability in the wood-pool relationships.

Salmonid habitat is limited in both quantity and quality in the Gualala River Watershed. Specifically, lack of instream wood and wood-formed pools has been identified as limiting factors. Understanding the relationship between wood and pools in the Gualala River watershed will help the GRWC strategize where and how they should focus future restoration and management efforts.

SECTION 5

Methods

5.1 Thalweg Surveys

This study incorporated data collected by GRWC during thalweg surveys of 37 different monitoring reaches throughout the watershed. These sites are a at least 1,000 ft long, but can ranging up to 2,500 ft in the larger tributaries. Thalweg surveys differ from longitudinal surveys in that the thalweg follows the deepest points along the length of a river, whereas longitudinal surveys may follow the centerline of the river. Longitudinal profiles have often been used by geomorphologists to determine stream gradient, whereas the thalweg profile can show the number of pools, depths of pools, pool-riffle spacing, and the spatial pattern of pool distribution (Madej 1999). Long-term monitoring of the thalweg profiles can reveal trends in aggradation or degradation (Madej 1999).

5.2 Metrics

Metrics for assessing wood loading were wood frequency (pieces per 1000 ft) and volume of wood in the bankfull channel (cu. ft. per 1000 ft). Bankfull is defined as the width of channel, past which overbank flooding begins. Wood pieces greater than 6 in diameter, and 4 ft long were included in this analysis.

Metrics for assessing the physical characteristics of pools were pool frequency (pools per 1000 ft), maximum pool depth (ft), and longitudinal pool area (ft^2). For pools, residual pool depths were used to account for differences in stage height between years. Residual pool depth is the difference in elevation between a point in the channel and the highest thalweg elevation downstream (Bathurst 1981, Lisle 1987). In a pool- riffle sequence, a residual pool depth is the depth of water in the pool below the elevation of the downstream riffle crest (Lisle 1995, Madej 1999). This can also be thought of as the isolated pool of water that would be present if there were no flow in the stream (Madej 1999). Only pools with residual pool depths greater than 1 ft were included in this analysis.

5.3 Changes over Time

Data collected by the GRWC at the four reference reaches (LNF1, PPW3, DRY3, and GUA1) provide a near-continuous picture of how the watershed is changing over time. Wood and pool metrics measured at these four reference reaches were used to characterize variability between years and between monitoring reaches from 1998 to 2010.

5.4 Wood-Pool Relationships

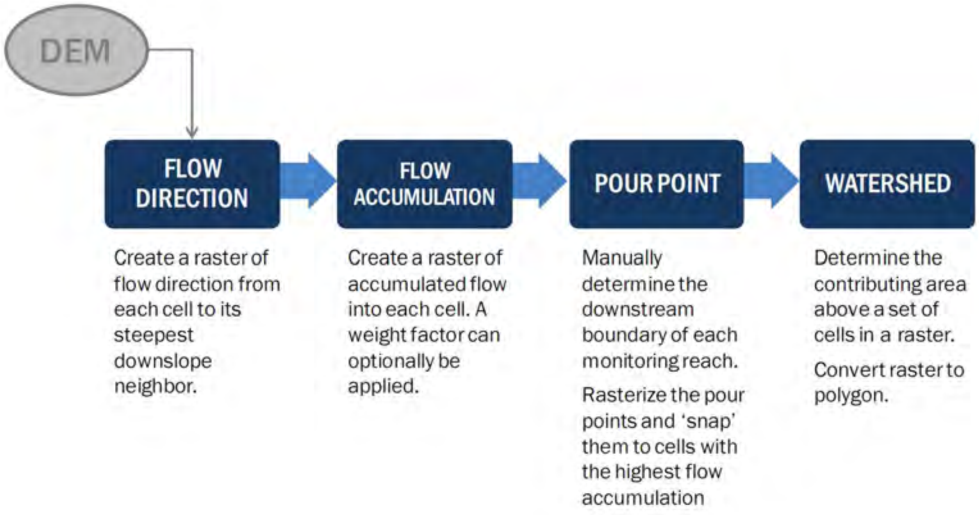
In order to assess the relationship between wood and pools, data for all 37 monitoring reaches were aggregated and linear regression used to establish the correlation between wood and pool metrics at the watershed scale. The four reference reaches were used to analyze the relationship at the reach-scale and to highlight differences observed between watershed-scale and reach-scale correlations.

5.5 Reach-specific Qualities

Reach-specific qualities were used as a partial attempt at explaining differences between wood-pool correlations observed at each of the reference reaches.

- Slope and canopy cover were collected as part of the GRWC thalweg surveys.
- Drainage area, drainage density, and road density were generated through a combination of GIS and analysis in Excel.
- Wood length-to-channel width was calculated based on data collected as part of the GRWC thalweg surveys.

The subbasin-scale analyses required delineating the upstream drainage area (contributing watershed area) of each of the four reference reaches (Figure 5-1). The delineated subbasins were used to determine the area draining to each reference



Create a raster of flow direction from each cell to its steepest downslope neighbor.

Create a raster of accumulated flow into each cell. A weight factor can optionally be applied.

Manually determine the downstream boundary of each monitoring reach.

Rasterize the pour points and 'snap' them to cells with the highest flow accumulation

Determine the contributing area above a set of cells in a raster.

Convert raster to polygon.

FIGURE 5-1.
Process for determining contributing watershed area.

reach. In addition, the delineated subbasins were used to clip existing layers of stream network and road network to get the length of streams and road in the contributing watershed area, which, when divided by the drainage area, yields drainage density and road density for each reference reach.

The process is rooted in the 10m DEM, from which direction of flow (Step 1) and then the flow accumulation (Step 2) are derived.

FLOW DIRECTION. Figure 5-2 shows the 10m DEM and Figure 5-3 shows the resulting flow direction. For every 3x3 cell cluster, the processor stops at the center cell and determines which of the adjacent cells is lowest –e.g., the direction of flow. Depending on the direction of flow, the output grid will have a cell value

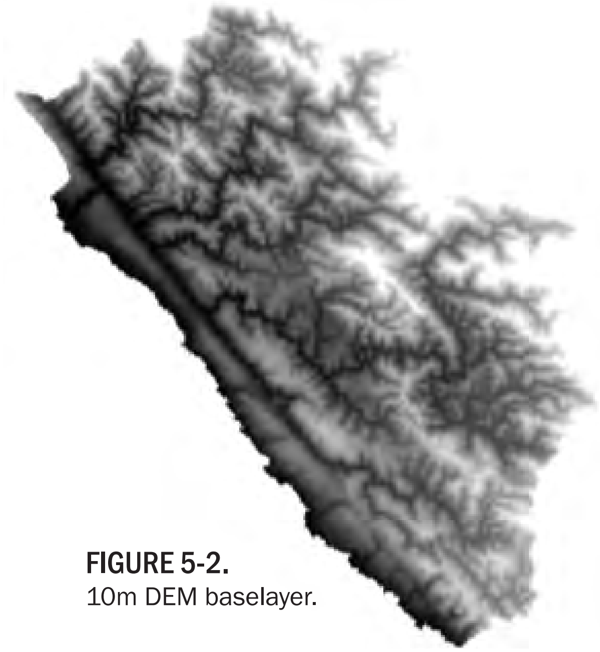


FIGURE 5-2.
10m DEM baselayer.

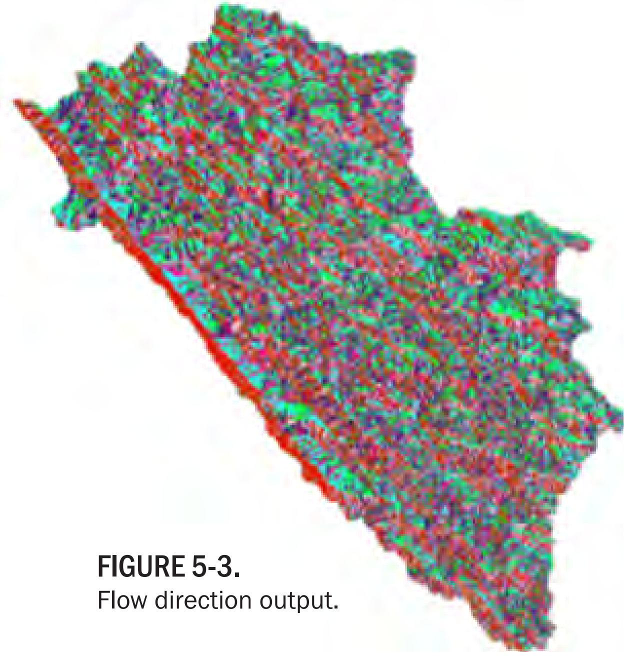
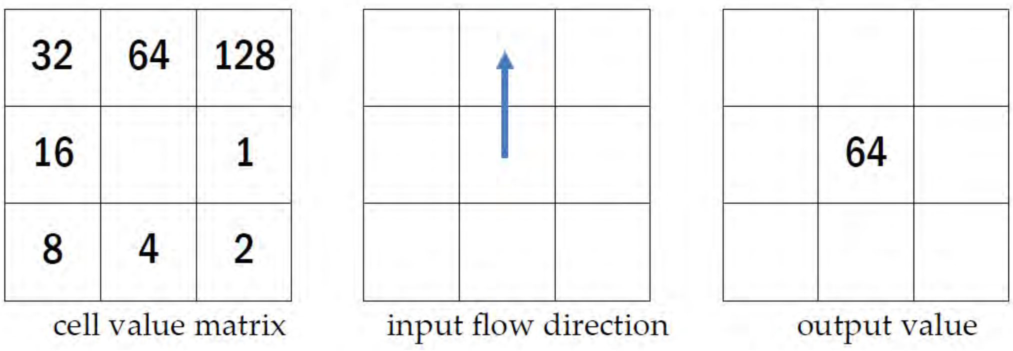


FIGURE 5-3.
Flow direction output.



32	64	128
16		1
8	4	2

FIGURE 5-4.
Schematic of how grid processing works in the Flow Direction tool. Adapted from course materials prepared for ESRM250 (University of Washington).

at the center cell, as shown in Figure 5-4. For example, if a cell flows northward, then in the output grid, the cell in its location will have a value of 64.

POUR POINTS. The pour points are the points in the stream network for which the contributing watershed area is being delineated. In this case, the downstream-most extent of the each monitoring reach are the pour points and. Initially, pour points were determined from the Gualala Monitoring Reach GIS layer (Figure 5-6). However, after calculating the flow accumulation, this initial set of pour points did not fall along the path of highest flow accumulation. Points were then manually shifted to better align with the path of highest flow accumulation.

WATERSHED. The Watershed Tool is applied as the final step in delineating the watershed area. The grid processor needs all three layers to generate the contributing watershed area above a set of cells in a raster: pour points, flow accumulation, and flow direction. The final step is to convert the raster output to polygon (Figure 5-7).

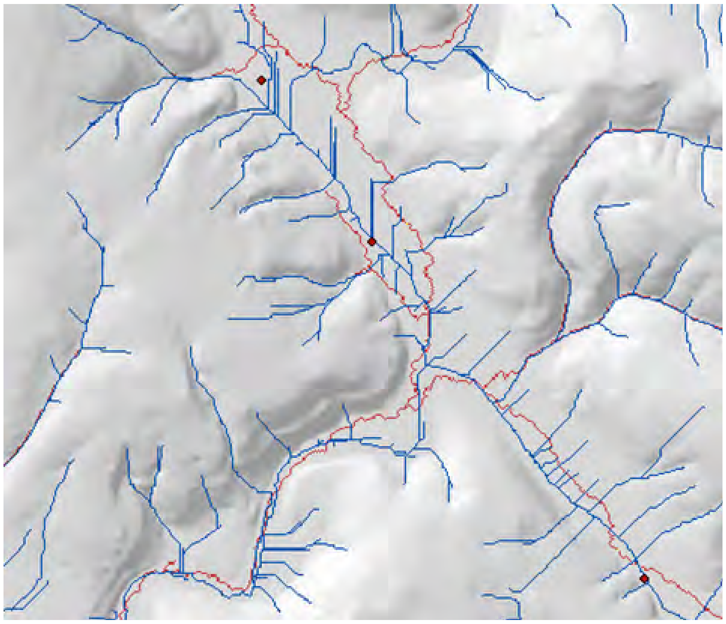


FIGURE 5-6.
Alignment of stream network (blue line) and path of highest flow accumulation (red line) showing that original pour points (red dots) fall outside of the path of highest flow accumulation.

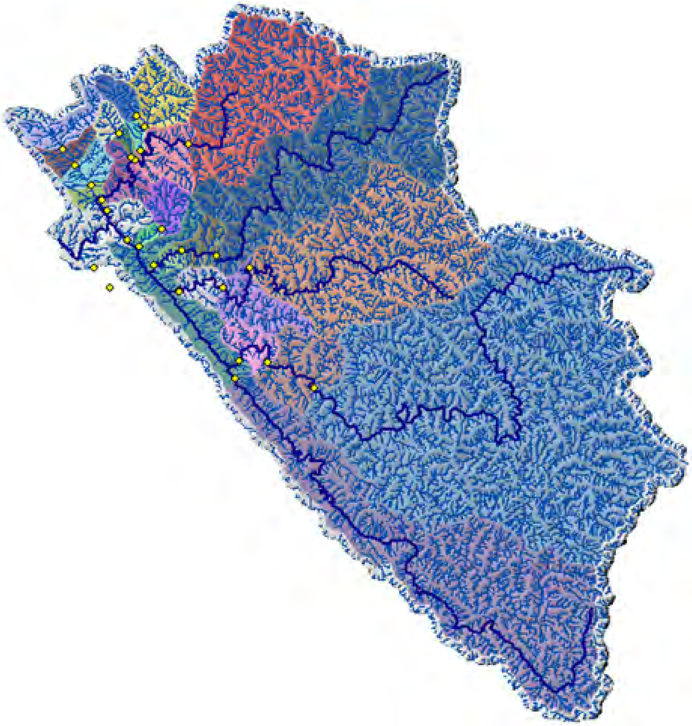


FIGURE 5 7.
Example of delineated watershed polygons.

SECTION 6

Results and Discussion

6.1 Tracking Wood and Pools Changes in the Watershed

6.1.1 Wood Density

Wood density (number of individual pieces of wood per 1000 ft) increased at all four reference reaches (Figure 6-1). While LNF1, PPW3 and DRY3 had relatively similar wood frequencies from 1998-2000, PPW3 had a faster rate of increase. Overall, PPW3 increased at a rate of 10.4 pieces per year, followed by LNF1 (6.6 pieces per year), DRY3 (5.5 pieces per year), and GUA1 (0.7 pieces per year).

There are no historical wood loading estimates for the Gualala to compare with current conditions. Examples of wood loading in unlogged forest can be a general guide for evaluating current conditions in lieu of a historical reference condition. In-stream wood characteristics compiled for California and Montana (West and West North Central United States) (Cordova et al. 2007) abundance ranges from 16 to 278, with an average of 99 pieces per 1000 ft. Based on Cordova et al. (2007), wood density levels in 2010 are above average at LNF1, PPW3, and DRY3.

In addition, wood loading from old-growth stands provide a benchmark against which recovery of previously disturbed streams may be compared (Flebbe and Dolloff 1995). Using wood density for managed (in the past 60–80 years) and unlogged (old growth) streams (Flebbe and Dolloff 1993), LNF1, DRY3, and PPW3 are above the average for streams in managed watersheds, but far below levels in unlogged forests (Figure 6-2).

Little North Fork, Gualala River Watershed

FIGURE 6-1.
Wood density (number of pieces per 1000 ft) at all four references reaches, 1998 to 2010.

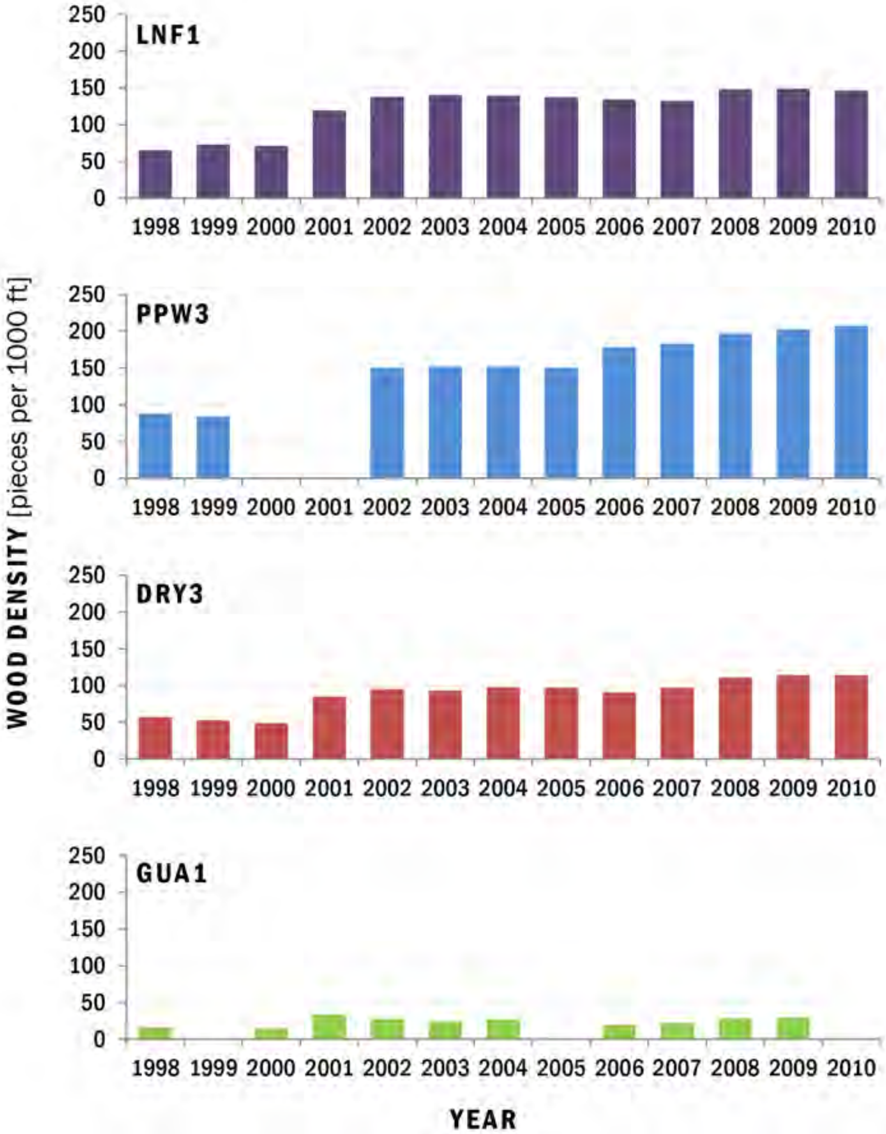
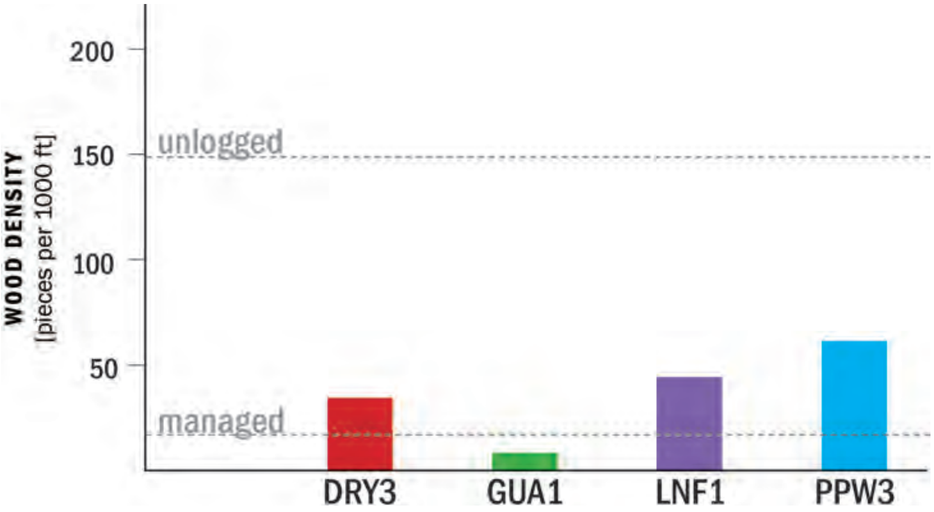


FIGURE 6-2.
The four reference reaches relative to estimates of wood density (pieces [>10 cm] per km) in managed and unlogged forest streams (Flebbe and Dolloff 1993).



6.1.2 Wood Volume

Wood volume (volume of wood [cu. ft.] in bankfull per 1000 ft) increased at all four reference reaches (FIGURE). While LNF1, PPW3 and DRY3 had relatively similar volumes from 1998–2000, again, PPW3 had a faster rate of increase. Overall, PPW3 increased at a rate of 760 cu. ft. per year, followed by DRY3 (390 cu. ft. per year), LNF1 (220 cu. ft. per year), and GUA1 (0.7 pieces per year).

In lieu of historical wood volume data for the Gualala River Watershed, wood volume was compiled from two studies (Benda et al. 2002, Maahs and Barber 2001) to provide a range of possible conditions for logged (second growth) and unlogged (old growth) forests (Figure 6-4). Benda et al. (2002) calculated large wood volume for 21 streams in northwestern coastal California: 5 old growth sites in Redwood National Park, and 16 sites in the Van Duzen watershed, while Maahs and Barber (2001) collected data on old growth and second growth forests along the northern California coast. Based on these two estimates, all DRY3, LNF1 and PPW3 are within the observed range for managed (second growth) forests (Figure 6-4). However, all reference reaches are below the average for streams in managed watersheds, and far below levels in unlogged forests.

Little North Fork, Gualala River Watershed

FIGURE 6-3.
Wood volume (cu. ft. of wood per 1000 ft) in the in the bankfull channel at all four references reaches, 1998 to 2010.

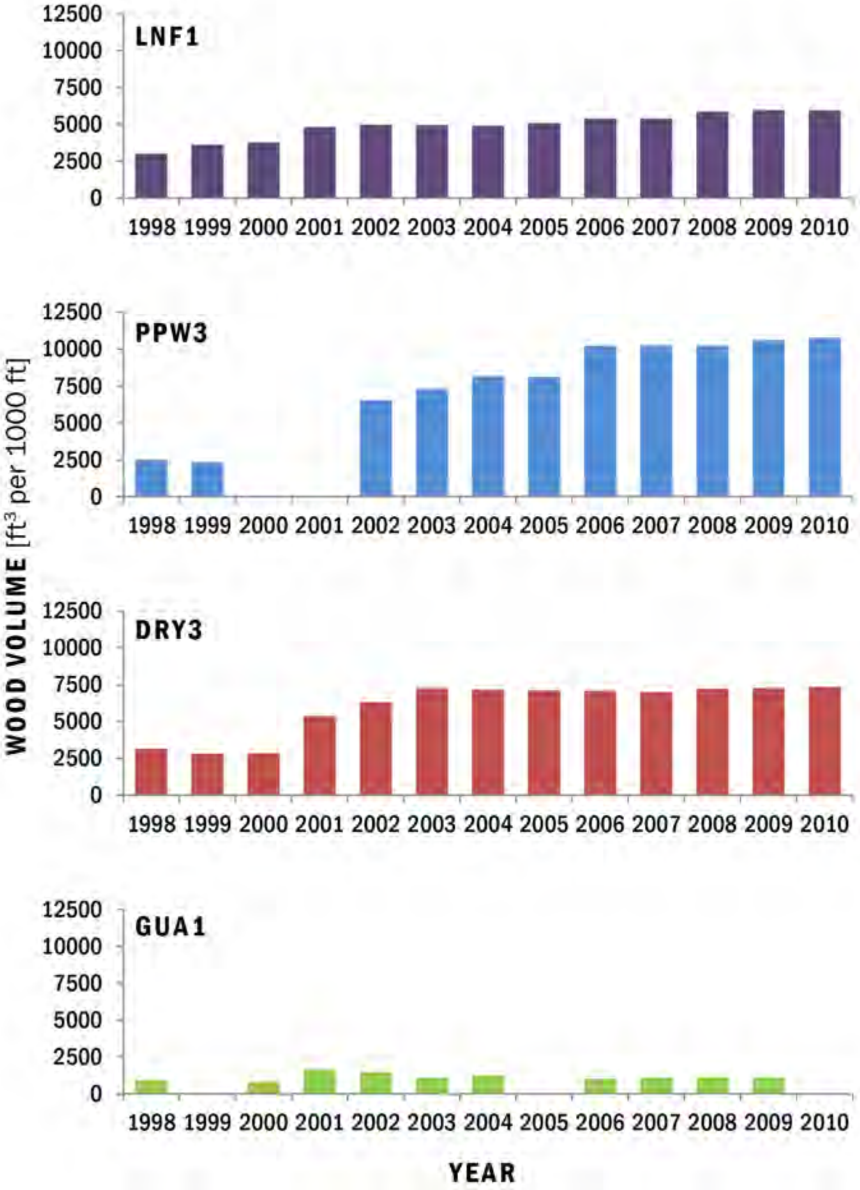
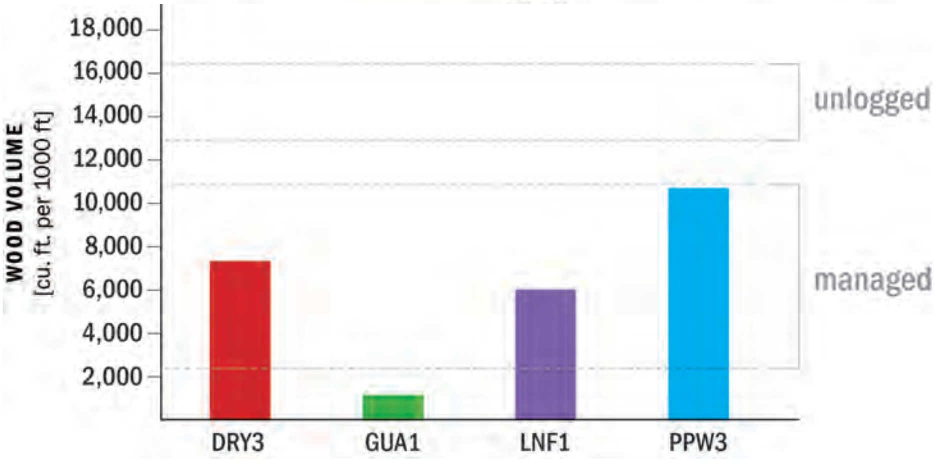


FIGURE 6-4.
The four reference reaches relative to estimates of wood volume (cu. ft. per 1000 ft) in managed and unlogged forest streams (Benda et al. 2002, Maahs and Barber 2001).



6.1.3 Pool Density

Pool density (number of pools >1 ft deep per 1000 ft) increased overall at LNF1 from 8 to 14 pools per 1000 ft (Figure 6-5). Pool density was more variable at PPW3, DRY3, and GUA1. PPW3 increases from 7 pools per 1000 m in 1998 to peak at 13 pools in 2005, but then declined in subsequent years. Conversely, DRY3 increased from 7 pools in 1998 to 8 pools in 2000, before declining to a low of 5 pools in 2005 and then peaking at 10 pools in 2009. Pool density at GUA1 remained consistently low throughout the period of record, never exceeding 3 pools per 1000 ft.

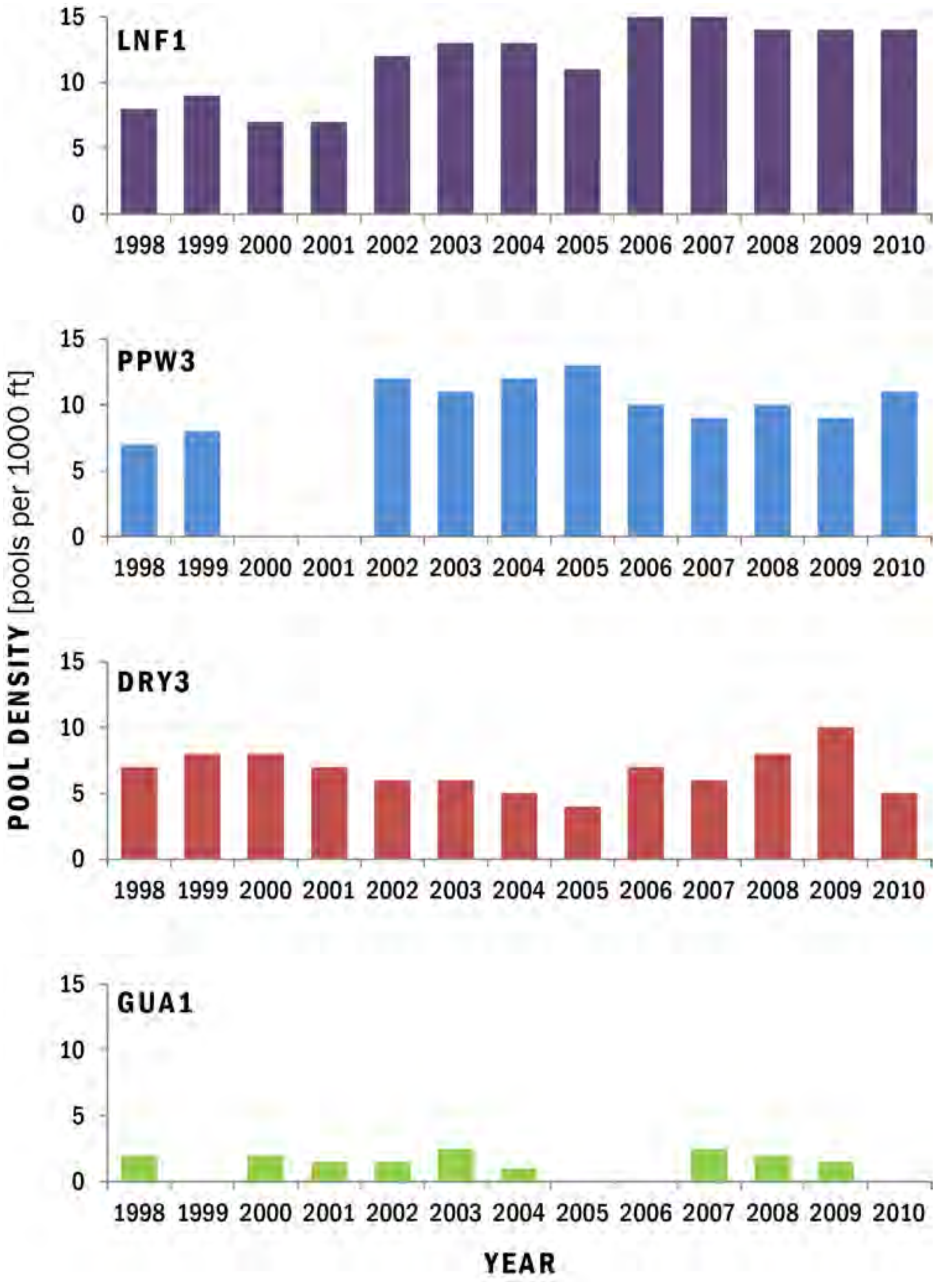


FIGURE 6-5. Pool density (number of pools per 1000 ft) at all four references reaches, 1998 to 2010.

6.1.4 Pool Area

GUA1 had the highest pool area (per 1000 ft) of the four reference reaches (Figure 6-6) but showed no overall trends for the period of record. Pool area at LNF1 showed initial declines in 2000 and 2001 before steadily increasing from 2002 onward. Pool area at PPW3 showed a gradual, but overall increase from 1998 to 2006, before steadily declining from 2006 onward. DRY3 appeared to follow a cyclic pattern of gradual declines followed by a sharp increase (in 2003 and 2008), and gradual decline.

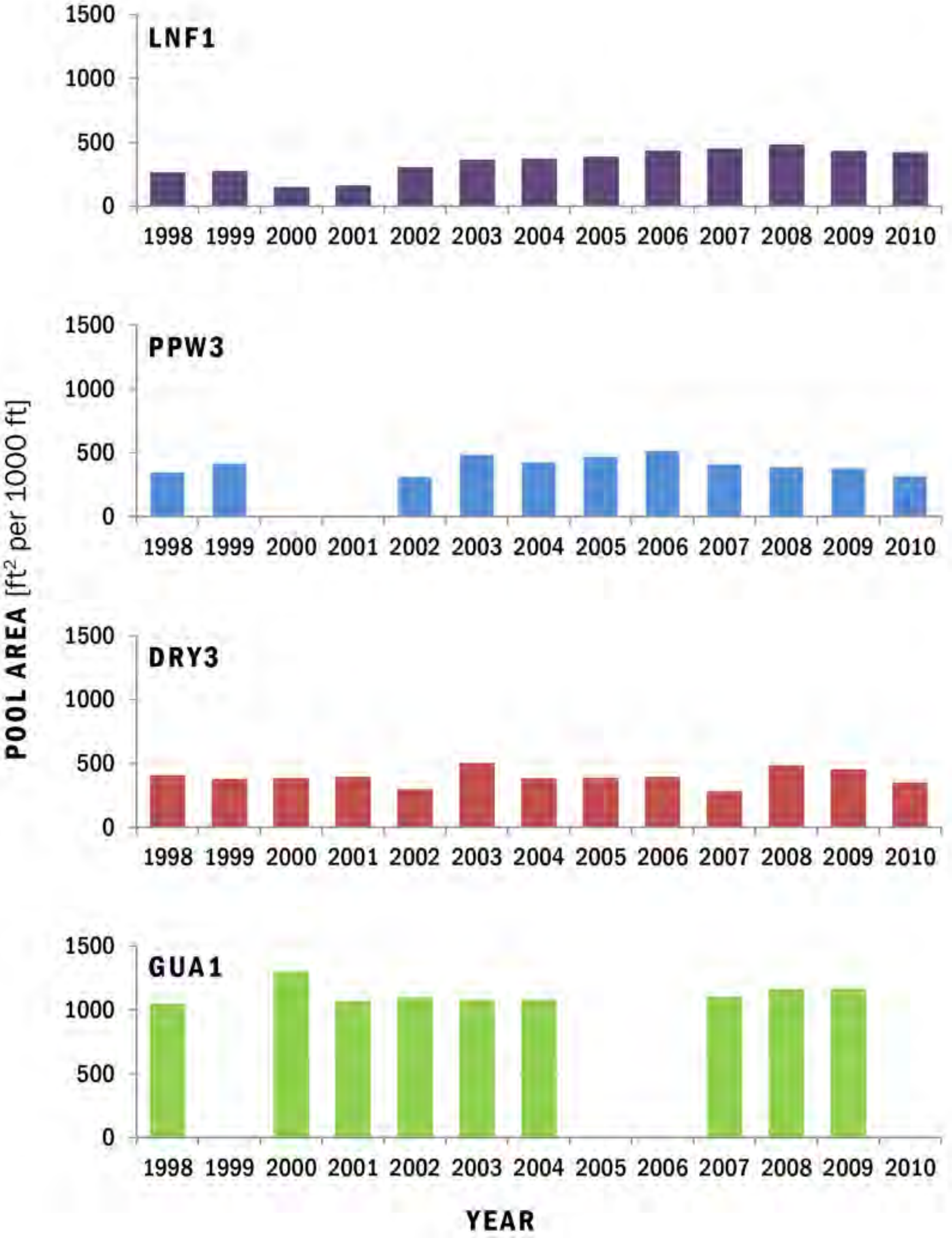


FIGURE 6-6. Pool area (ft^2 per 1000 ft) at all four references reaches, 1998 to 2010.

6.1.5 Maximum Depth

There were no observable patterns in maximum pool depths (ft) at PPW3, DRY3, or GUA1 (Figure 6-7). LNF1 showed an overall step-wise increase in maximum pool depth from 1.98 ft in 1998 to 3.85 ft in 2010. The step-wise pattern observed at LNF1 suggests that a major event occurred in 2002, followed by gradual pool-filling, and then another major pool-forming event in 2007, and subsequent filling.

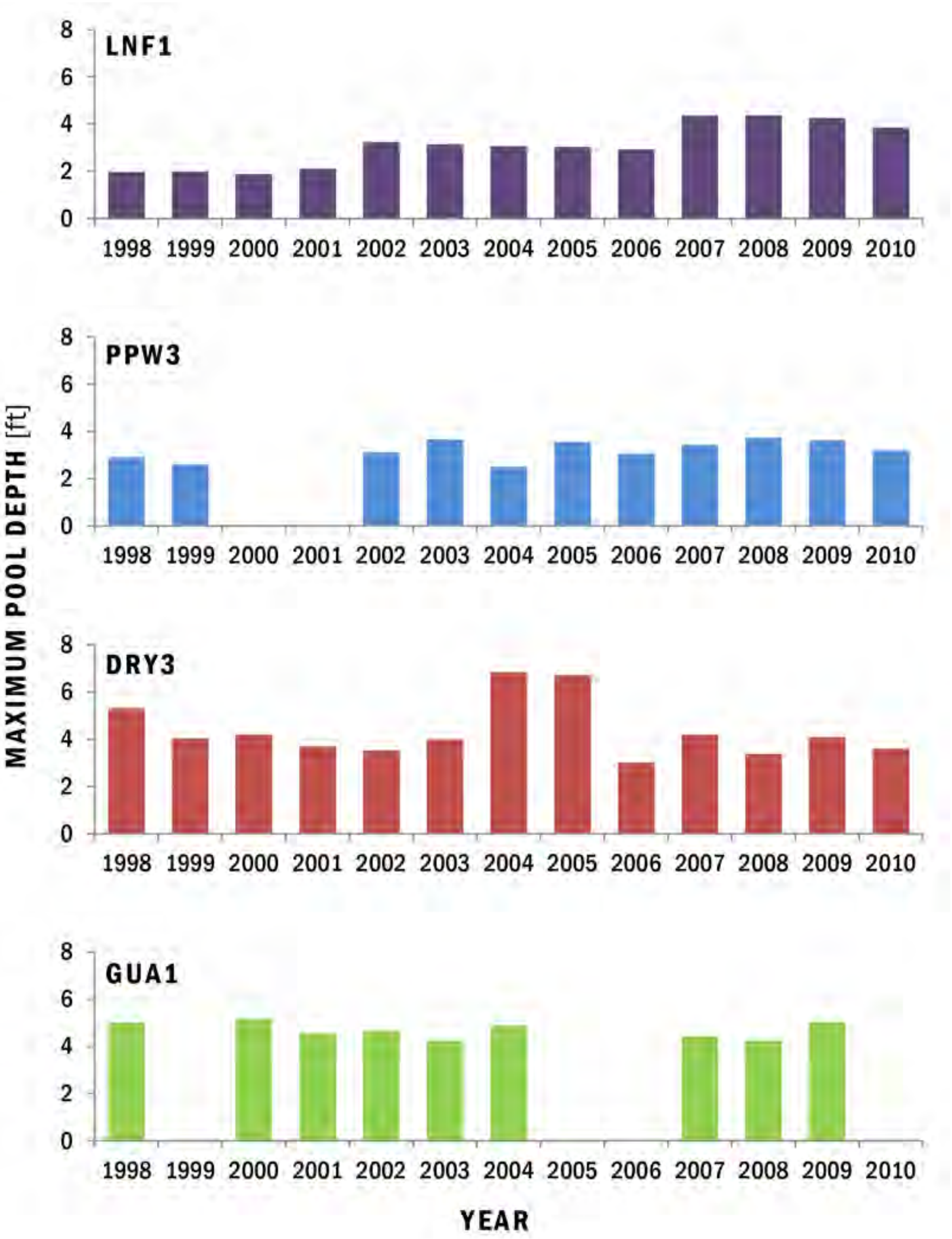


FIGURE 6-7. Maximum pool depth (ft) at all four references reaches, 1998 to 2010.

6.2 Linear Model Analysis

6.2.1 Do Increases in Wood Increase Pool Habitat?

Pool metrics (dependent variable) were correlated against wood metrics (independent variable) to determine wood-pool relationships. All wood and pool data for all 37 monitoring reaches were aggregated to observe the overall trend at the watershed scale.

Each pool metric exhibited the same correlation with wood volume as it did with wood density (Figure 6-8 and 6-9). A positive relationship was expected for each wood-pool relationship however, pool frequency was the only pool metric that exhibited a strong positive correlation with both wood volume and wood density ($p<0.001$) at the watershed level. There was a moderate negative correlation between pool area and both wood metrics ($p<0.001$), and a slight negative correlation between maximum pool depth and both wood metrics ($p<0.001$).

At the reach-scale, trends observed at individual reference reaches sometimes differed from the overall watershed trend. For example, there was a positive correlation between pool density and wood density at the aggregated watershed level, however, at the reach-scale both GUA1 and DRY3 showed slight negative correlations. In general, regardless of the pool or wood metric, GUA1 and DRY3 exhibited slight negative correlations, while PPW3 exhibited slight positive correlations. Only LNF1 exhibited strong positive correlations for all wood-pool metrics.

2011 thalweg survey in progress at Big Pepperwood Creek.

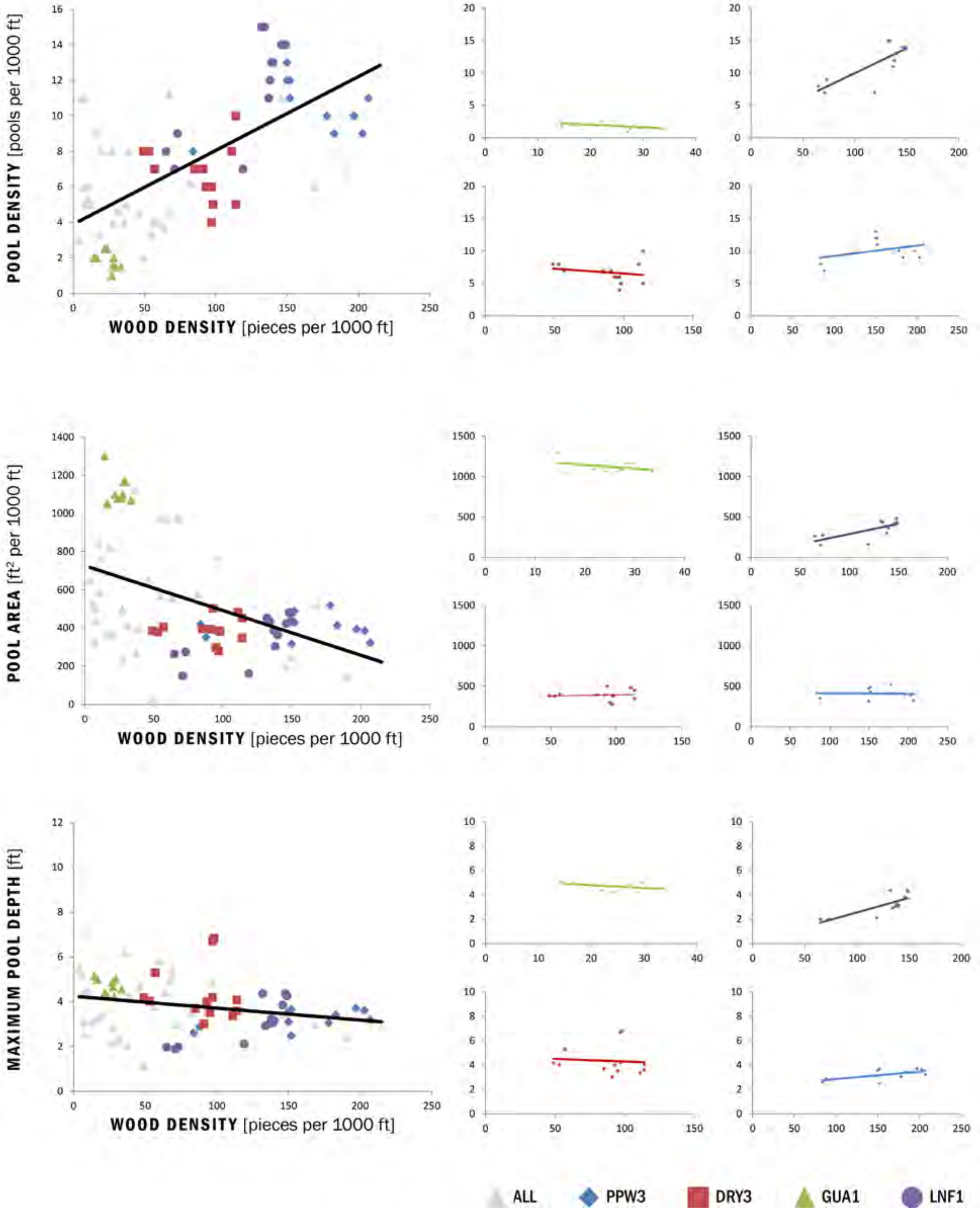


FIGURE 6-8.
Pool density (top), pool area (middle), and maximum pool depth (bottom) by wood density for all 37 monitoring reaches, 1998-2010. Each of the reference reaches are indicated in aggregated watershed chart (left) and then shown individually (right).

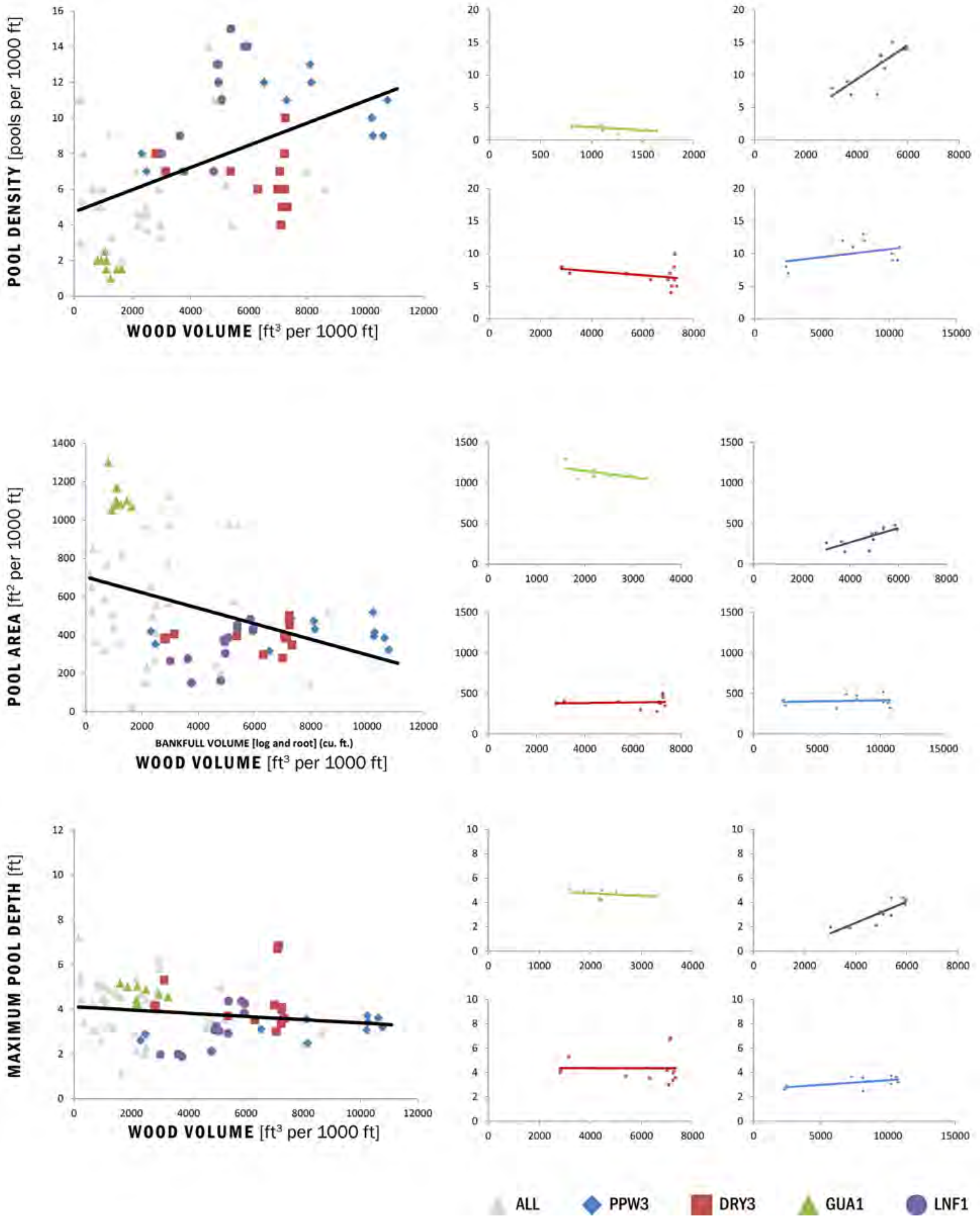


FIGURE 6-9.

Pool density (top), pool area (middle), and maximum pool depth (bottom) by wood volume for all 37 monitoring reaches, 1998-2010. Each of the reference reaches are indicated in aggregated watershed chart (left) and then shown individually (right).

6.3 Can Reach-specific Qualities Explain the Observed Variability in the Wood-Pool Relationships?

Several characteristics specific to each reference reach were derived to partially explain why the wood-pool relationship at LNF1 (and to some extent PPW3) differed drastically from the other three reference reaches (Table 6-1), or conversely, why the other three reference reaches did not exhibit the expected relationship between wood and pools.

TABLE 6-1.
Summary table of metrics specific to each of the reference reaches.

Metric	Units	Reference Reach			
		LNF1	PPW3	DRY3	GUA1
SUBBASIN CHARACTERISTICS					
Drainage Area	mi^2	3.10	2.85	6.42	246.25
Drainage Density	mi/ mi^2	6.85	6.54	6.94	7.25
Road Density	mi/ mi^2	8.38	6.88	6.18	4.63
WOOD CHARACTERISTICS*					
Avg. Wood Length	ft	15.7	15.5	16.6	20.0
Avg. Length of Keyed Piece	ft	16.3	16.3	19.9	20.1
Max. Wood Length	ft	80	80	60	75
Avg. Diameter	in	15.8	18.5	19.8	16.8
CHANNEL CHARACTERISTICS**					
Bankfull Depth (D)	ft	1.92	3.15	1.66	3.65
Bankfull Width (W)	ft	27.7	25.2	40.2	123.3
W:D	--	14.4	8.0	24.2	33.8
Cross-sectional Area	ft^2	55.8	88.6	68.3	411.6
Slope	%	1.46	1.46	0.77	0.09
Canopy Cover***	%	89	88	77	17

*All wood characteristics are for the portion of wood in the bankfull channel.
**Channel characteristics are averaged across 2008–2010 cross-section and thalweg surveys.
***Canopy cover measured at the center of the channel during 2010 surveys.

6.3.1 Subbasin Characteristics

Drainage Area

In general for the Gualala River Watershed, as drainage area increases, pool area increases while pool density decreases (Figure 6-10). In accordance with this overall trend, we see that GUA1 drains a much larger area than the other four

TABLE 6-2.

Characteristics of the subbasin area draining to each of the reference reaches.

Metric	Units	Reference Reach			
		LNF1	PPW3	DRY3	GUA1
SUBBASIN CHARACTERISTICS					
Drainage Area	mi^2	3.10	2.85	6.42	246.25
Drainage Density	$mi/\ mi^2$	6.85	6.54	6.94	7.25
Road Density	$mi/\ mi^2$	8.38	6.88	6.18	4.63

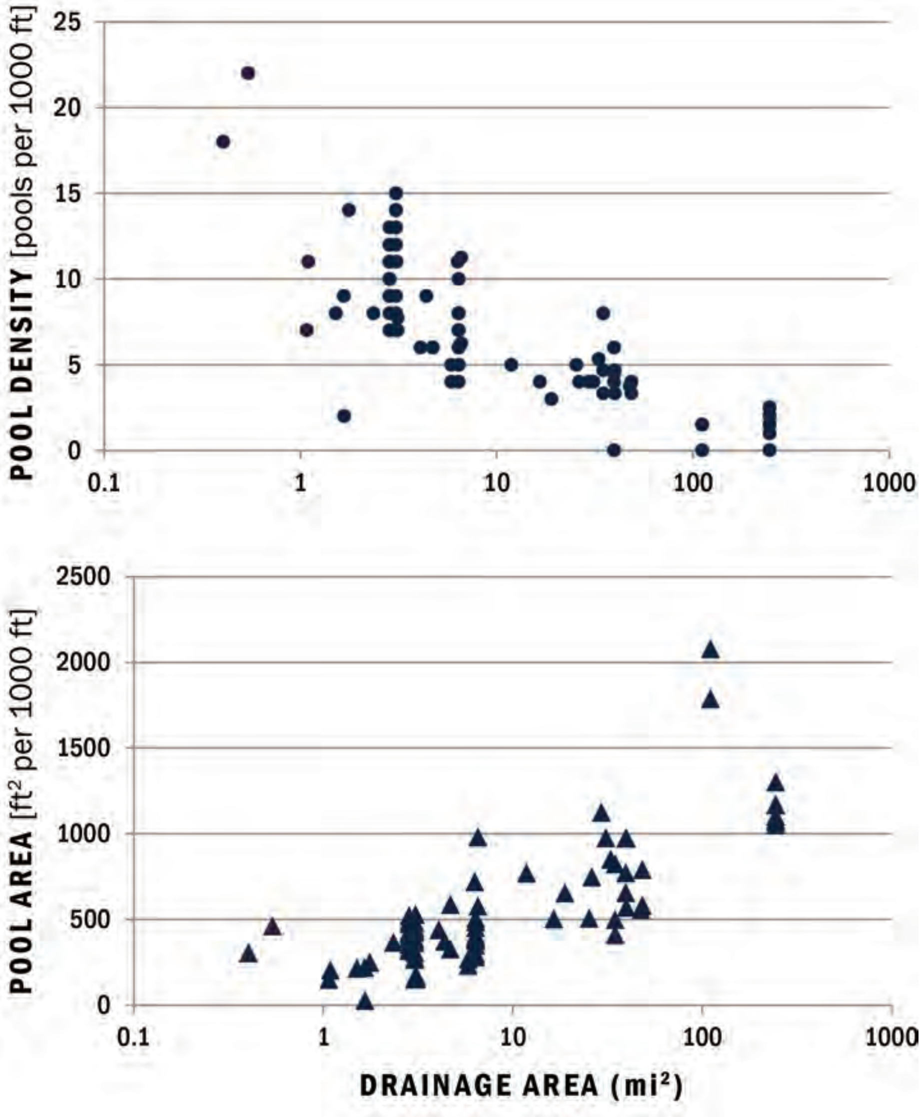


FIGURE 6-10.

Pool density (top) and pool area (bottom) by drainage area for all 37 monitoring reaches, 1998–2010. (Note: The x-axis is log-scale) reference reaches (246.25 mi^2), has the lowest pool frequency, but the highest pool area (Table 6-2). DRY3 is higher in the watershed and drains a smaller area (6.42 mi^2). PPW3 drains the smallest area (2.85 mi^2), though LNF1 is similar in size (3.10 mi^2).

There was no discernible correlation between wood volume or wood density and drainage area (Figure 6-11).

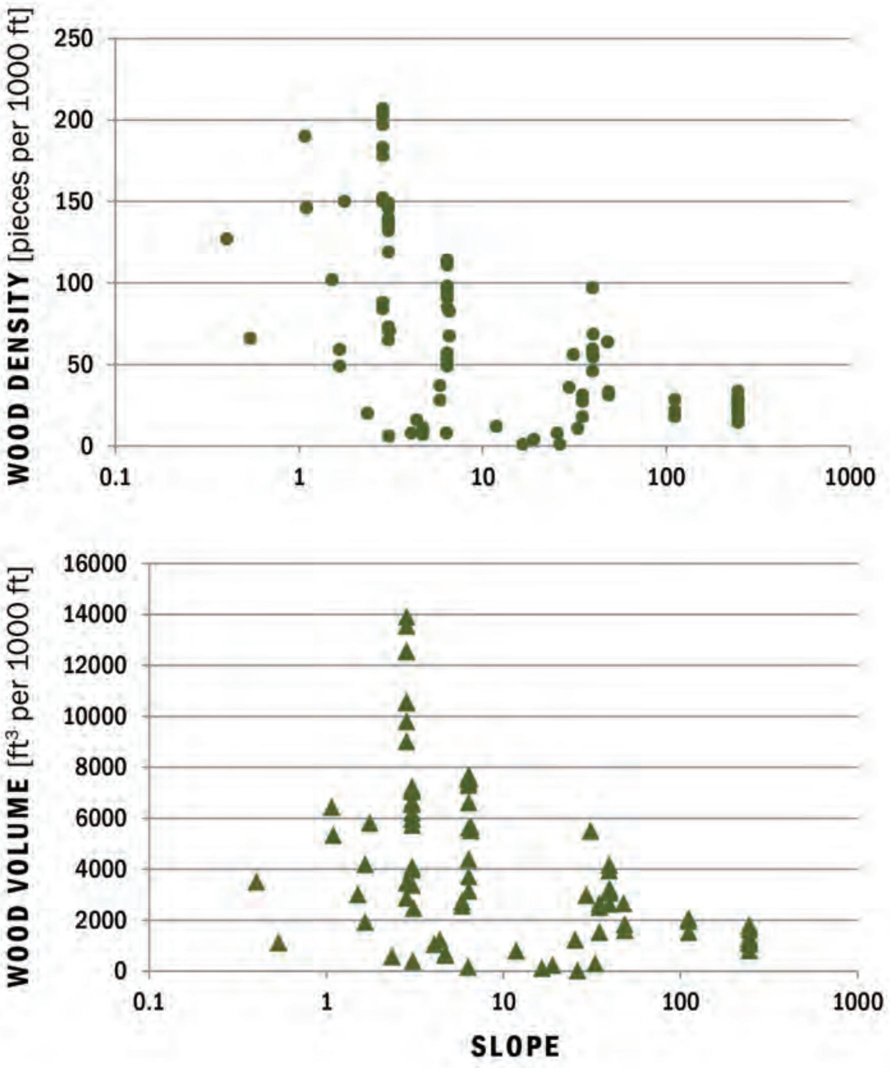


FIGURE 6-11.
Wood density (top) and by wood volume (bottom) by drainage area for all 37 monitoring reaches, 1998–2010. (Note: The x-axis is log-scale)

Drainage Density

Drainage density (length of stream per unit area) was calculated to understand the extent to which the contributing subbasin is dissected by surface streams, and the efficiency with which water is discharged (Knighton 1998). LNF1 and PPW3 have similar drainage areas, however LNF1 has higher drainage density (Figure 6-12, Table 6-2) suggesting that runoff is discharged faster to the stream, and further suggesting that LNF1 may be more hydraulically responsive than PPW3.

Road Density

In addition, road density (length of roads per unit area) was calculated to give some guidance as to potential sediment sources discharged to the stream. As previously stated, in the Gualala River Watershed, 85% of anthropogenic sediment input is road-relate suggesting that subbasins with higher road densities would have greater sediment yields. The U.S. Forest Service (USFS) characterizes road density levels greater than 1.7 mi/mi^2 as "High" and greater than 4.7 mi/mi^2 as "Extremely High" (Quigley et al. 1996). By this classification both LNF1,

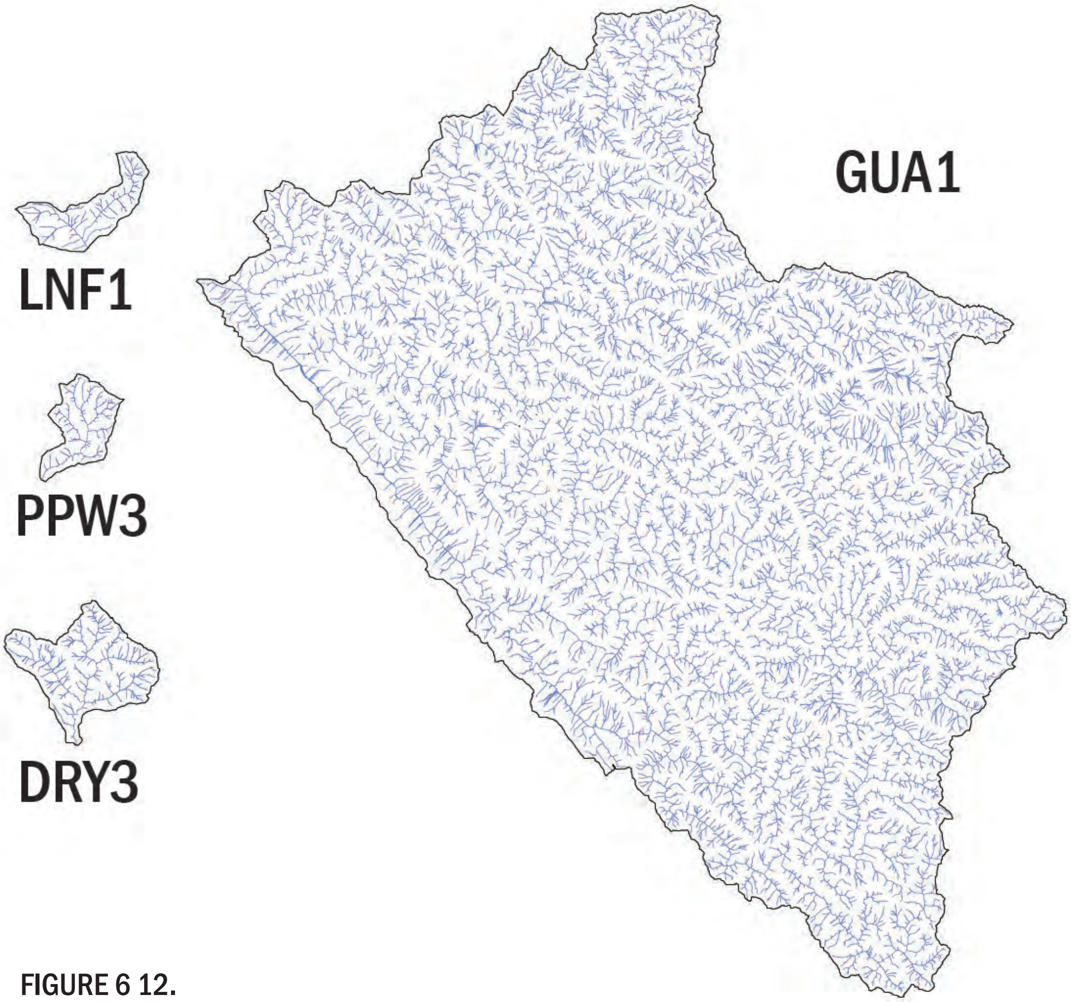


FIGURE 6 12.
Drainage density for the four reference reaches.

PPW3, are DRY3 have "Extremely High" road densities, while GUA1 is only considered "High."

If we directly compare LNF1 and PPW3 (similar drainage areas), LNF1 has a much higher road density than PPW3 (8.38 mi/mi^2 and 6.88 mi/mi^2 respectively) (Table 6-2) (Figure 6-13). This suggests that large wood in LNF1 may exert a stronger influence on pool formation and sediment storage than in PPW3.

6.3.2 Comparison of Wood and Channel Dimensions

The scale of wood to the surrounding channel underscores the role of wood in small, medium, and large streams (Gurnell et al. 2002). In small streams, wood pieces themselves dominate the hydrological and sediment transfer characteristics. In medium streams, wood length and form and the ability to form larger accumulations is more critical. In large streams, wood dynamics vary with the geometry of the channel, channel pattern and distribution of flow velocities (Gurnell et al. 2002).

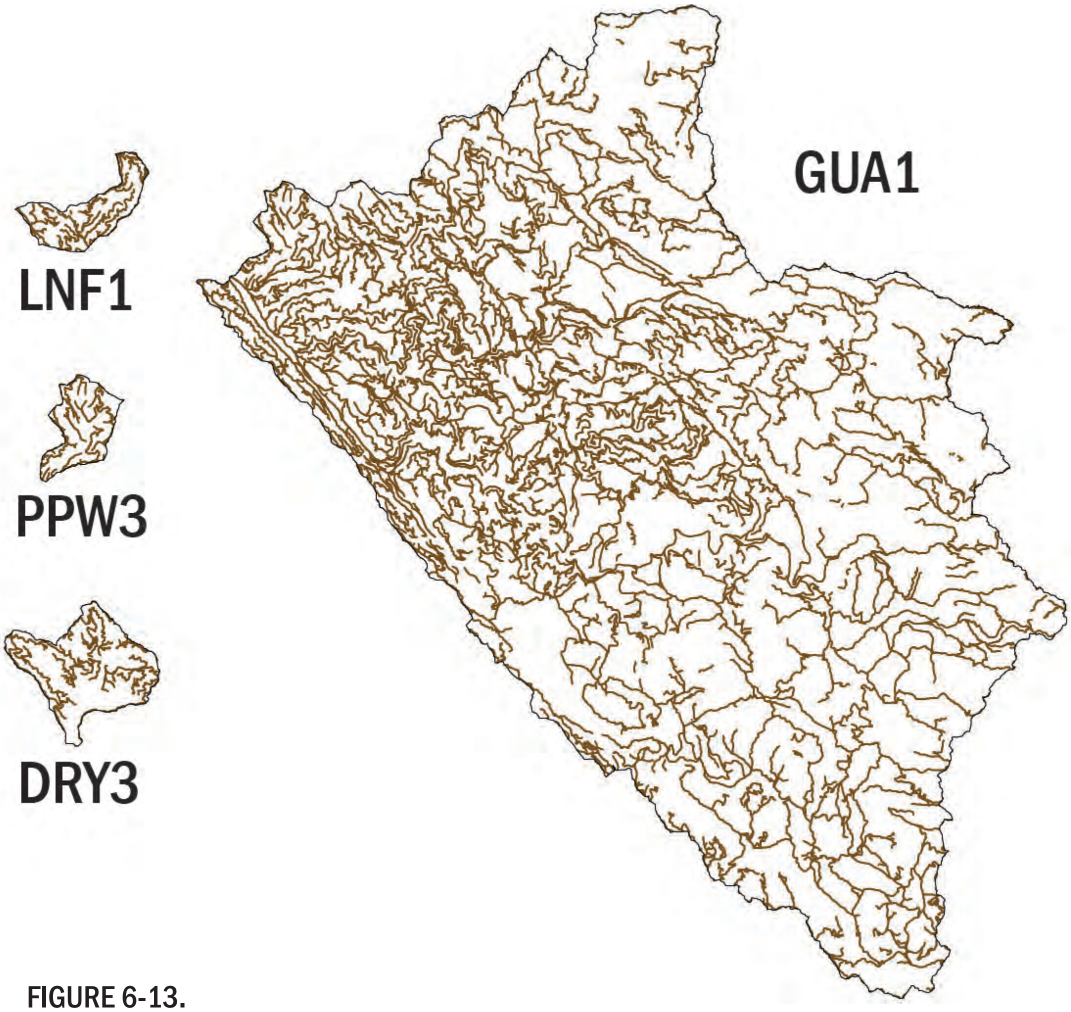


FIGURE 6-13.
Road density for the four reference reaches.

Wood Dimensions

Among the reference reaches, GUA1 had the highest average wood length (in bankfull) at 20.0 ft, followed by DRY3 (16.6 ft). LNF1 and PPW3 had similar wood lengths at 15.7 ft and 15.5 ft respectively (Table 6-3).

Among the reference reaches, DRY3 had the widest diameter wood (19.8 in), followed by PPW3 (18.5 in), and GUA1 (16.8 in). LNF1 had the smallest average diameter of the four reference reaches (15.8 in) (Table 6-3).

The key to establishing a logjam are wood pieces that serve as the anchors for the logjam structure (keyed pieces). Keyed pieces were overall wider and longer than the average for each reach (Table 6-4). Among the reference reaches, keyed pieces in GUA1 were the longest (20.0 ft), followed by DRY3 (19.9 ft), and then LNF1 and PPW3 (16.3 ft each) (Table 6-4).

TABLE 6-3.
Wood dimensions for each of the reference reaches, 1998-2010.

Metric*	Units	Reference Reach			
		LNF1	PPW3	DRY3	GUA1
WOOD CHARACTERISTICS*					
Avg. Wood Length	ft	15.7	15.5	16.6	20.0
Avg. Length of Keyed Piece	ft	16.3	16.3	19.9	20.1
Max. Wood Length	ft	80	80	60	75
Avg. Diameter	in	15.8	18.5	19.8	16.8

*All wood characteristics are for the portion of wood in the bankfull channel.

TABLE 6-4.
Dimensions of keyed pieces for each of the reference reaches, 1998-2010.

Metric*	Units	Reference Reach			
		LNF1	PPW3	DRY3	GUA1
KEYED PIECES					
Avg. Wood Length	ft	16.3	16.3	19.9	20.0
Avg. Diameter	in	21.0	21.0	21.7	18.3

*All wood characteristics are for the portion of wood in the bankfull channel.

Channel Characteristics

Bankfull Width and Depth

Though GRWC has cross-section data dating back to 1998, bankfull width and depth was only recorded starting in 2008. The values in Table 6-5 were generated by averaging bankfull width and depth at the three cross-sections for each reach from 2008–2010.

Drainage area has a linear relationship with stream order (Knighton 1998). Given the large drainage area of GUA1, we would assume GUA1 was a higher stream order than the other three reference reaches and should therefore be a larger stream. In fact, bankfull depth and width at GUA1 was the deepest and widest of the four reference reaches (Table 6-5). Larger channels are able to pass wood more easily—small pieces are flushed downstream, leaving mostly large pieces (Naiman et al. 2002).

In a smaller system, a wider range of wood sizes may be able to influence flow (Bilby and Ward 1989). LNF1 and PPW3 were much narrower (27.7 ft and 25.2 ft respectively) though LNF1 was shallower (1.92 ft compared with PPW3 at 3.15 ft) which suggest they are more responsive to perturbations caused by instream wood.

Channel Gradient (Slope)

In general for the Gualala River Watershed, as slope decreased, pool area increased while pool density decreased (Figure 6-14). In accordance with this overall trend, GUA1 also had the lowest percent slope (0.09%) which is to be expected of reaches lower in a watershed.

TABLE 6-5.
Channel characteristics specific to each of the reference reaches.

Metric	Units	Reference Reach			
		LNF1	PPW3	DRY3	GUA1
CHANNEL CHARACTERISTICS**					
Bankfull Depth (D)	ft	1.92	3.15	1.66	3.65
Bankfull Width (W)	ft	27.7	25.2	40.2	123.3
W:D	--	14.4	8.0	24.2	33.8
Cross-sectional Area	ft^2	55.8	88.6	68.3	411.6
Slope	%	1.46	1.46	0.77	0.09
Canopy Cover***	%	89	88	77	17

*Channel characteristics are averaged across 2008-2010 cross-section and thalweg surveys.
**Canopy cover measured at the center of the channel during 2010 surveys.

Beechie and Sibley (1997) found that pool spacing was more sensitive to the presence of wood in moderate-slope channels than in low-slope channels. LNF1 and PPW3 had a steeper gradient at 1.46% (Table 6-5). Steeper gradient streams provide more opportunity for the formation of plunge pools (Bilby and Ward 1989) which may partially explain the higher pool densities observed at LNF1 and PPW3 (Figure 6-5).

There was no discernible correlation between wood volume or wood density and drainage area (Figure 6-15).

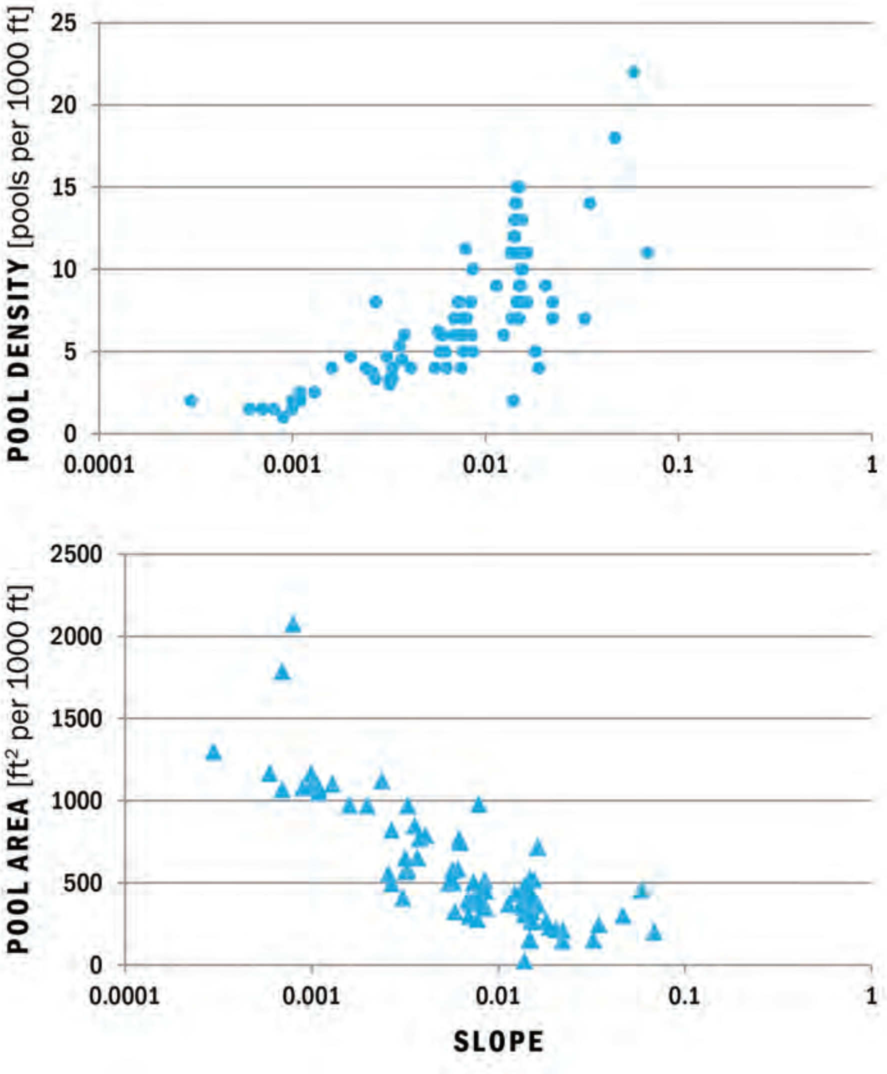


FIGURE 6-14.
Pool density (top) and pool area (bottom) by slope for all 37 monitoring reaches, 1998–2010. (Note: The x-axis is log-scale)

Canopy Cover

Canopy cover was assessed as a surrogate for understanding wood recruitment potential. Areas with higher canopy cover would suggest more trees on the adjacent banks that could be contributed or branches that would fall into the channel. However, it is only meaningful to compare similarly sized streams—in this case, LNF1 and PPW3, which have similar canopy cover (89% and 88% respectively) (Table 6-5).

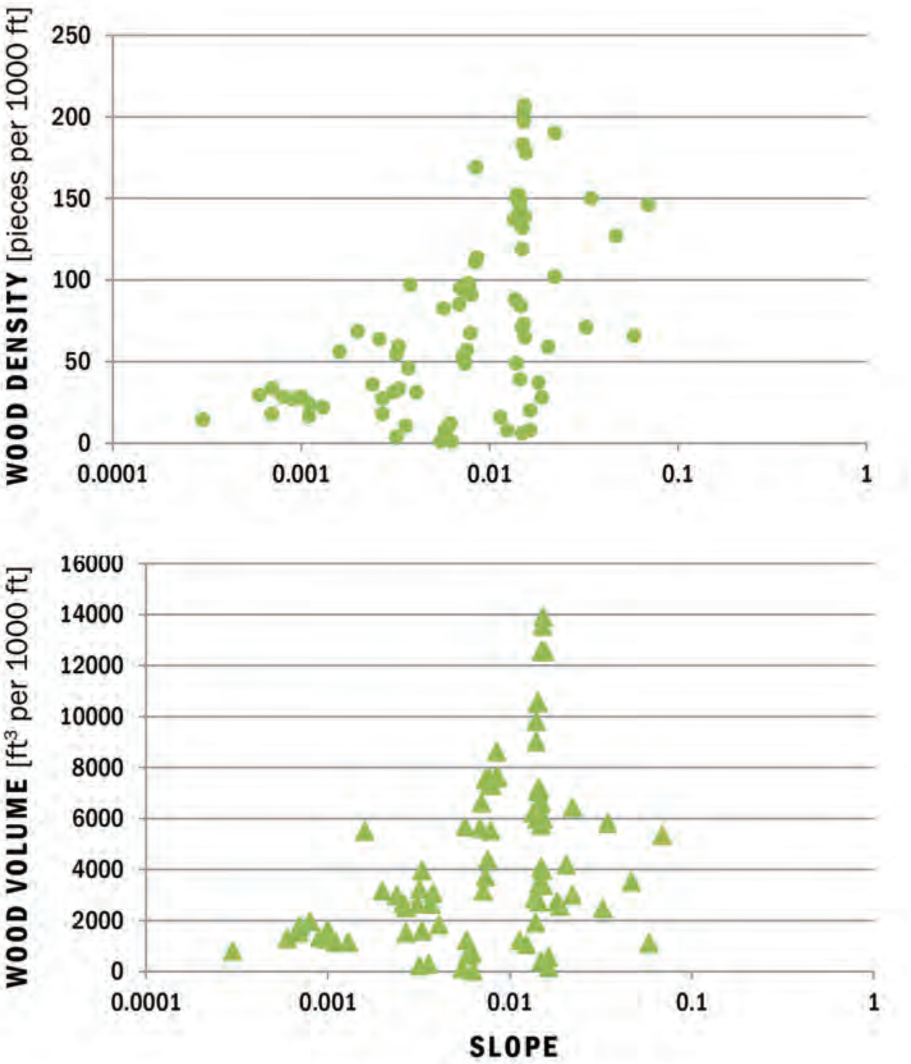


FIGURE 6-15.

Wood density (top) and wood volume (bottom) by slope for all 37 monitoring reaches, 1998-2010. (Note: The x-axis is log-scale)

Cross-sectional Area

Using a simplified rectangular cross-section shape, cross-sectional area is calculated as average bankfull width by average bankfull depth. LNF1 and PPW3 have been similar in almost every characteristic assessed. However, in looking at the cross-sectional area LNF1 had the smallest cross-sectional area (55.8 ft^2) (Table 6-5). Despite PPW3 being narrower than LNF1, PPW3 was deeper and overall had a comparatively larger cross-sectional area (88. ft^2). As would be expected based on previous analyses, GUA1 had the largest cross-sectional area (463.9 ft^2).

Wood Dimensions-to-Channel Characteristics

The typical definition of large wood does not take into consideration wood stability relative to channel size and stream power. Further, Beechie and Sibley (1997) recommend using the interaction between channel width and wood abundance should to interpret relationships between channel characteristics, wood abundance, and pools. In isolation, the size and diameter of wood pieces or channel characteristics alone do not inform our understanding of wood-pool dynamics. But by looking at the two in combination we can begin to understand how wood may be interacting with the channel, specifically, looking at what distinguishes LNF1 from the other reference reaches.

Thinking about the channel as the chute through which wood flows, it is helpful to think about cross-section area relative to the size of the wood in the system. The number of pools within a reach is often related to the frequency of obstructions that initiate or enhance pool development (Montgomery et al. 1995, Buffington et al. 2002). Intuitively, a larger piece of wood moving through a narrower chute has a greater potential to get caught on something and wedged into place, which then has greater potential to form pools and larger wood accumulations.

Using the average length and diameter (in bankfull) of wood pieces in each reference reach we can calculation a piece's cross-sectional area. This represents the piece's maximum potential to obstruct flow if it were placed perpendicular to flow. Occupying a larger portion of the bankfull cross-sectional area should result in more hydraulic diversity and more pools, in addition to increasing the potential to trap additional wood pieces and create jams. At LNF1, wood occupied a greater portion of the channel cross-section (50%) than any of the other reference reaches (Table 6-6, Figure 6-16).

The goal, however, is to understand how this characteristic actually relates to pool formation. When the wood-to-bankfull channel ratio was correlated with the average pool density for the same period of time (2008–2010) there was a strong positive relationship (Figure 6-17).

TABLE 6-6.
Comparison of wood and channel cross-sectional area, 2008-2010.

REFERENCE REACH	CROSS-SECTIONAL AREA (ft^2)		RATIO (wood:channel)
	Wood (in bankfull)	Bankfull Channel	
LNF1	27.7	56	0.50
PPW3	32.1	89	0.36
DRY3	29.2	68	0.43
GUA1*	24.1	412	0.06

*GUA1 was not surveyed in 2010. The values reported are for 2008, and 2009 only.

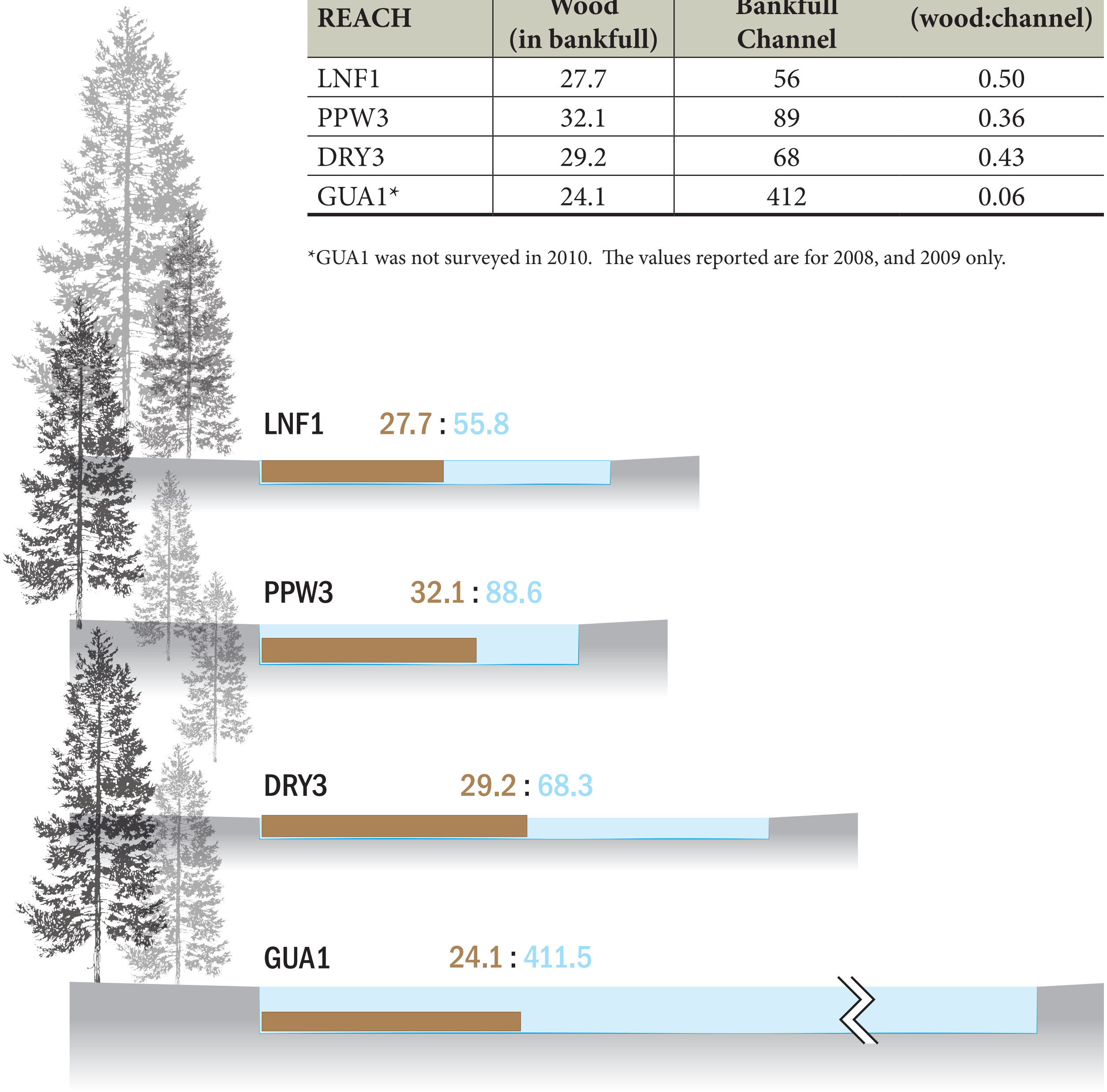


FIGURE 6-16.
Comparison of wood cross-section area with channel cross-section area for each of the reference reaches.

Though this relationship was based on only three years of data and four reaches, the analysis suggests that when strategizing wood placement for pool-formation purposes, GRWC should consider the cross-sectional area of the wood relative to the channel to increase their chances of improving pool density.

Pools can be formed by mechanisms other than wood. Bends, outcrops, rooted bank projections, and obstructions other than large wood are common instream obstacles thought to govern pool formation (Lisle 1986b). In order to qualitatively assess whether pools were associated with wood pieces the wood locations along the thalweg profiles of LNF1 and DRY3 were marked for all the period of record (Figure 6-18). Tighter spacing of vertical lines indicates areas of wood clusters which are usually associated with the deepest and largest pools.

A more detailed look at the number of pieces at each location along the thalweg expands and enforces the connection between the amount of wood and the area and depth of the pool (Figure 6-19 and 6-20). This pattern suggests that the wood dispersed throughout a reach may not be as important for pool formation as denser concentrations of wood at spot locations along the thalweg profile.

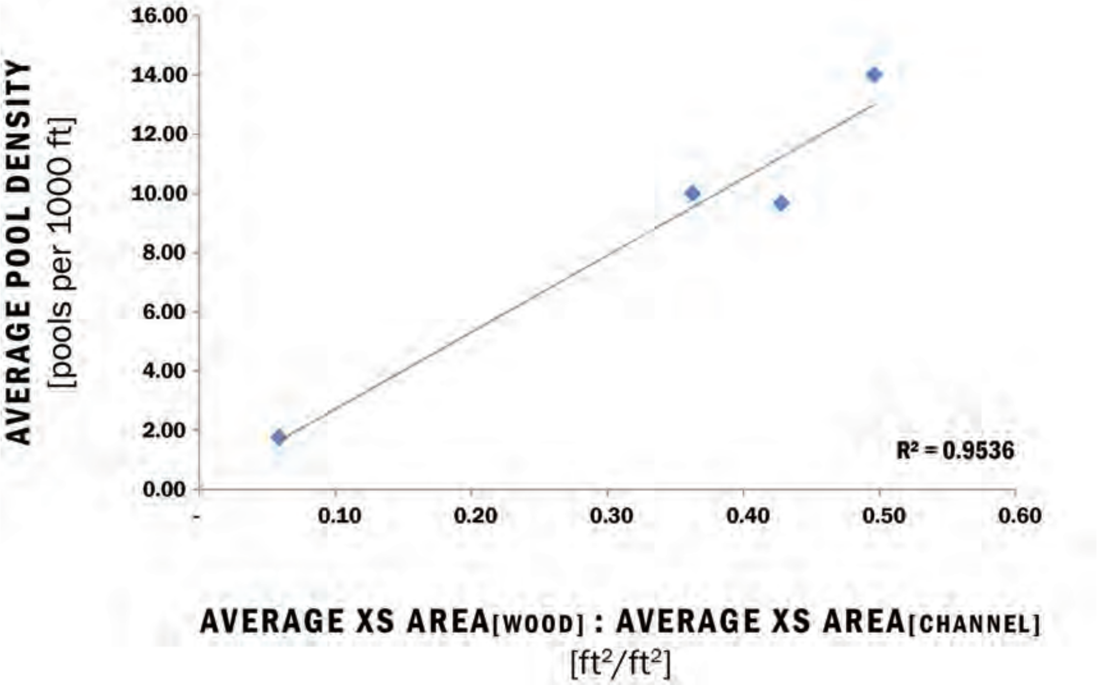


FIGURE 6-17.
Average pool density relative to the portion of the bankfull channel, 2008-2010.

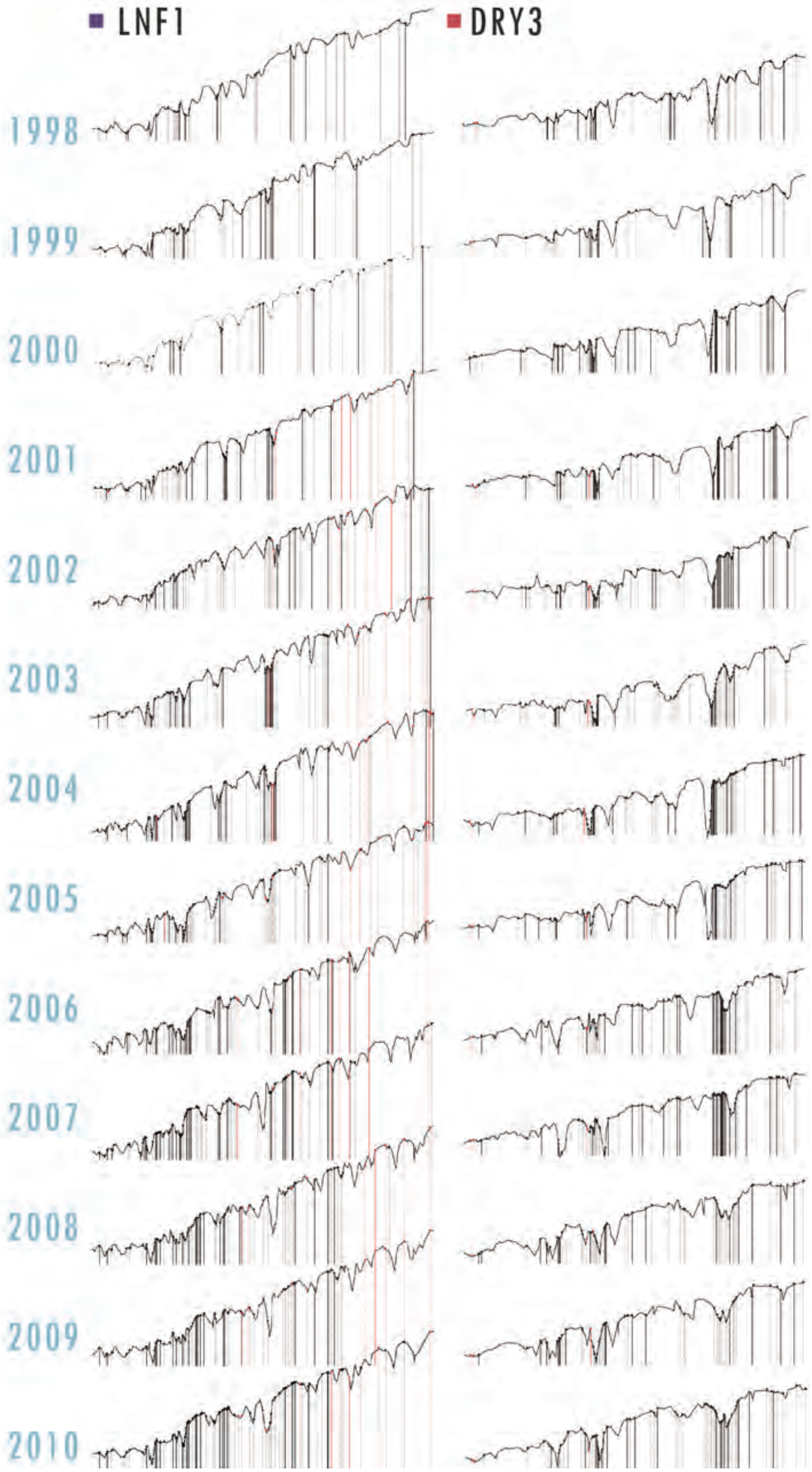


FIGURE 6-18.
Spacing of wood pieces along the thalweg profile for LNF1 (left) and DRY3 (right), for all the periods of record. Dots represent wood pieces along the profile, and the vertical lines indicate the concentration of wood.

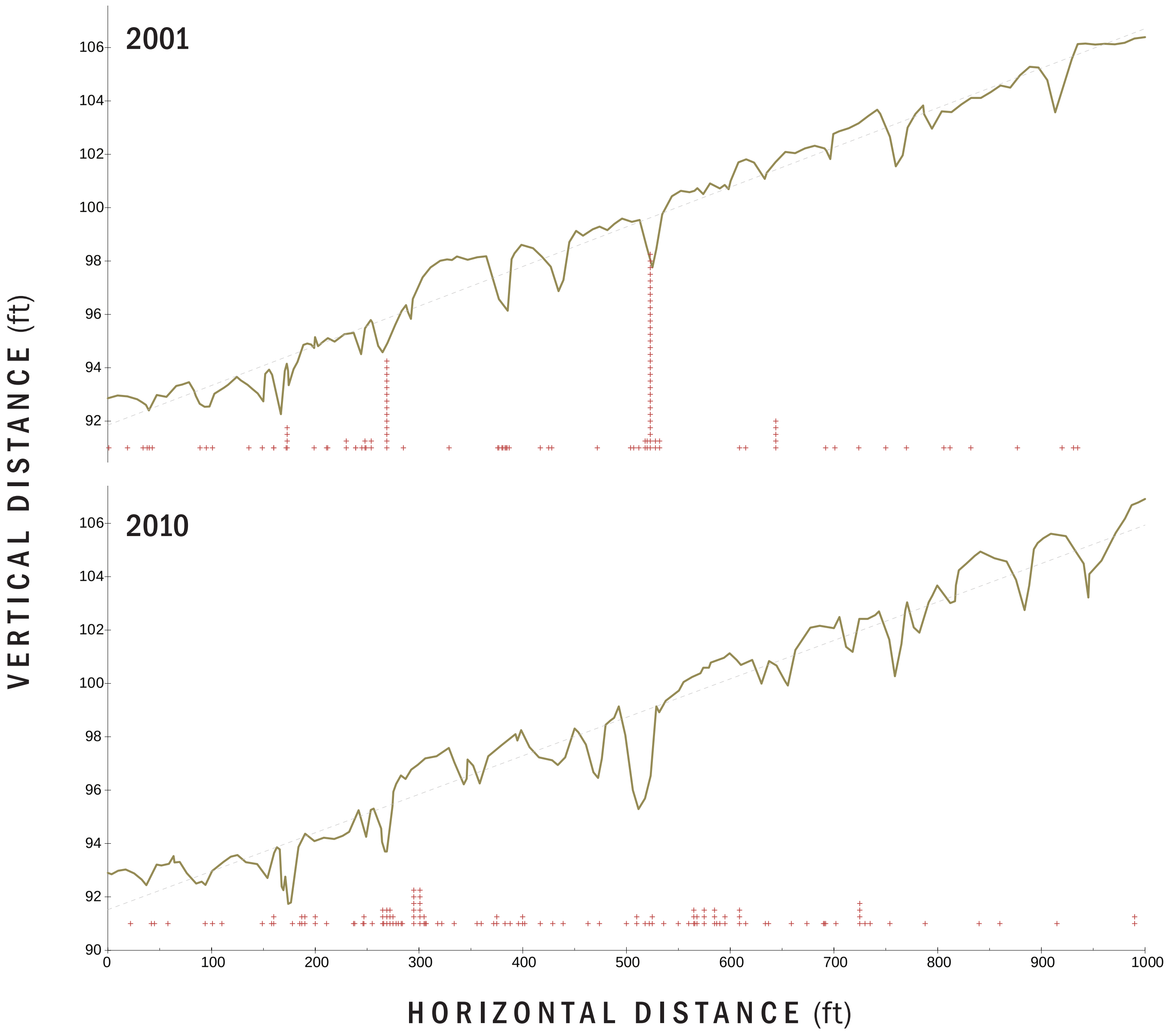


FIGURE 6-19. Concentration of wood pieces along the thalweg profile for LNF1 for 2001 (top) and 2010 (bottom). Red markers indicate wood pieces along the profile.

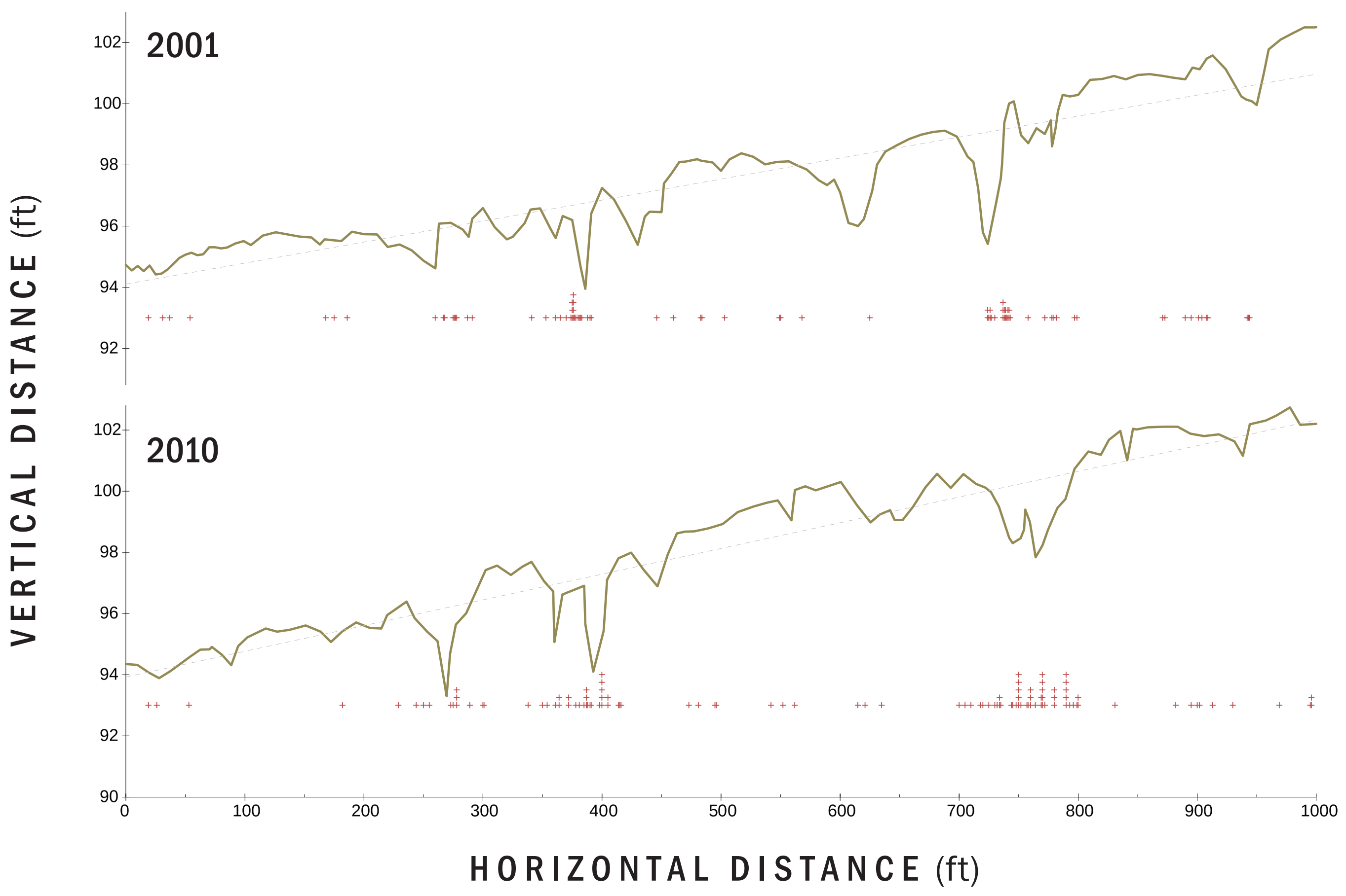


FIGURE 6-20. Concentration of wood pieces along the thalweg profile for DRY3 for 2001 (top) and 2010 (bottom). Red markers indicate wood pieces along the profile.

SECTION 7

Conclusions & Recommendations

This study confirmed that there are parts of the Gualala River Watershed that are increasing in both wood and pool abundance. However, in looking at the four reference reaches, there is a lot of variation between years and between reaches. This highlights the need for continuous, long-term monitoring throughout the watershed to more accurately assess changes over time.

In looking at the relationship between pools and wood at the aggregated watershed-scale, pool density was positively correlated with wood abundance (wood volume and wood density), pool area was negatively correlated with wood abundance, and maximum pool depth showed a slight negative correlation.

At the reach-scale, the relationship between pools and wood at each reference reach sometimes differed from the overall trend at the watershed-scale. Of the four reference reaches, LNF1 exhibited a positive relationship between all pool metrics and wood abundance. LNF1 has the smallest cross-sectional area of the four reference reaches. Based on this differentiating quality, it appears that the size of the wood piece relative to the channel cross-sectional area may be key to effective creation of wood-formed pools.

An analysis of wood locations along thalweg profile suggest that perhaps the concentration of the wood may be more important to pool formation than individual pieces dispersed throughout the reach.

This study examined wood-pool relationships at three different scales of analysis and highlights the importance of doing data analysis at broad and fine scales. Potentially important patterns can get lost when data is aggregated at broader scales. In the case of this study, management decisions made at the aggregated watershed-scale may be different than decisions based on the four reference reaches, which in turn may be different than decision based on details observed in the thalweg profile.

As the GRWC moves forward with their wood placement projects, they should consider the size of the wood relative to the channel cross-sectional area. Furthermore, they should consider placing wood in denser concentrations along the thalweg rather than distributing wood throughout the reach. Finally, the overarching goal of the wood placement projects is to improve instream conditions for coho and steelhead salmon. This study has shown that increasing wood can result in more pool habitat. However, fish response to the created habitat is the ultimate criteria for success. The GRWC should add a fish monitoring component to their monitoring that matches the rigorous work they are already doing with their wood inventory and thalweg surveys.

From a restoration science perspective, information on wood-pool dynamics may help GRWC and other practitioners understand the physical dimensions that lead to wood accumulations, and the relative importance of different reach-specific characteristics in facilitating pool formation using large wood. This information could be used to identify and prioritize portions of the channel network that are more conducive for creating pool habitat for anadromous salmonids, or for supporting other ecological functions.

SECTION 8

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